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TNO report

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UAVs and control delays

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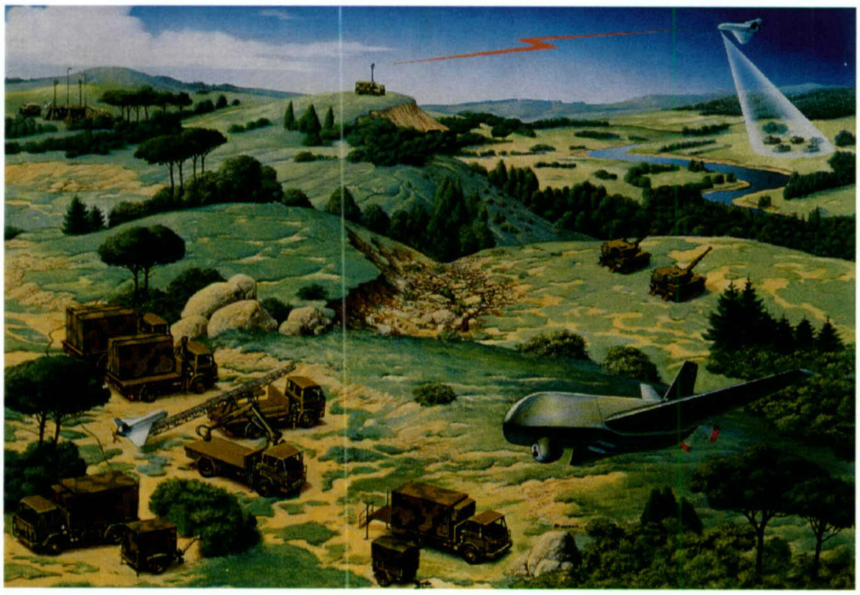
UAVs and control delays

"Unmanned Aerial Vehicles worden op afstand aangestuurd via een verbinding die een flinke vertraging kan introduceren. Hoe groot kan die vertraging worden en wat is eigenlijk nog acceptabel?"



Probleemstelling

UAV's (Unmanned Aerial Vehicles) worden vanuit een GCS (Ground Control Station) op afstand aangestuurd. Vanwege de aard van de verbinding van deze twee eenheden is er altijd sprake van een zekere mate van vertraging van de stuursignalen van het GCS naar de UAV en van de feedback (telemetrie en sensorinformatie) van de UAV naar het GCS. Deze vertragingen kunnen een invloed hebben op de kwaliteit van de aansturing van de UAV.

De Koninklijke Luchtmacht bezint zich op een mogelijke aanschaf van UAV's. Het is daarbij van belang te weten welke beperkingen de verschillende verbindingen opleveren en welke mogelijke oplossingen mogelijk zouden zijn. TNO voerde binnen het programma Nieuwe Generatie Gevechtsvliegtuigen een onderzoek uit specifiek gericht op het gebied van signaalvertragingen. Overige aspecten van de verbinding (bijvoorbeeld bandbreedte, continuïteit van de verbinding, ruis en betrouwbaarheid) maakten geen deel uit van de onderzoeksopdracht.

Beschrijving van de werkzaamheden

Onze werkzaamheden bestonden uit het verwerken van literatuur met betrekking tot mogelijke bronnen van vertraging en rekenwerk op dit gebied, het verwerken van literatuur op het gebied van effecten van vertraging op de menselijke prestatie en literatuur op het gebied van mogelijke oplossingen voor de problematiek die de vertragingen opleveren.

Resultaten en conclusies

Het gevonden bereik van vertragingen voor de verschillende operatiewijzen van UAVs is zeer groot. De bijbehorende effecten op de prestatie van de bestuurder variëren van net meetbaar tot onacceptabel. Er zijn echter diverse compensatiemethoden die het bereik van de acceptabele vertragingen flink kunnen oprekken.

Toepasbaarheid

De resultaten zijn bruikbaar in het UAV-verwervingsproces. Het is voorstelbaar dat bijvoorbeeld een keuze gemaakt moet worden uit een systeem dat direct moet worden aangestuurd (als een vliegtuig) of een systeem dat meer op basis van supervisie wordt aangestuurd. De resultaten van de studie kunnen, samen met gegevens over de door de KLu gewenste

verbindingswijze, aangeven of het platform nog acceptabel aan te sturen is en daarmee dus een valide kandidaat is.

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Samenvatting

Vraagstelling:
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De Koninklijke Luchtmacht bezint zich op een mogelijke aanschaf van UAV's. Het is daarbij van belang te weten welke beperkingen de verschillende verbindingen opleveren en welke mogelijke oplossingen mogelijk zouden zijn. TNO voerde binnen het programma Nieuwe Generatie Gevechtvliegtuigen een onderzoek uit specifiek gericht op het gebied van signaalvertragingen. Overige aspecten van de verbinding (bijvoorbeeld bandbreedte, continuïteit van de verbinding, ruis en betrouwbaarheid) maakten geen deel uit van de onderzoeksopdracht.

Werkwijze:
Onze werkzaamheden bestonden uit het verwerken van literatuur op het gebied van de mogelijke bronnen van vertraging en enig rekenwerk op dit gebied, het verwerken van literatuur op het gebied van effecten van vertraging op de menselijke prestatie en literatuur op het gebied van mogelijke oplossingen voor de problematiek die de vertragingen opleveren.

Resultaten:
Afhankelijk van de specifieke situatie blijken vertragingen tussen de 100 en 1600 ms (en meer) op te kunnen treden. Dit is aanzienlijk, aangezien er bij 100 ms al meetbare verslechtering van de menselijke stuurprestatie optreedt, en er bij een vertraging van 250-300 ms in het geval van vliegtuigbesturing al meestal van een onacceptabele verlaging van de vliegkwaliteiten sprake is. Er blijken echter technieken te zijn (filtering en voorspellende displays) die het traject van de acceptabele vertraging kunnen oprekken tot zo'n 400 ms of meer. Dit laatste geldt voor de handmatige besturing van de UAV zelf. De handmatige besturing van camera's aan boord van UAV's is aanzienlijk minder kritisch en zal waarschijnlijk tot ruim voorbij de 1000 ms via genoemde aanpassingen tot een acceptabel resultaat kunnen leiden.

Conclusies:
Bij directe verbindingen tussen GCS en UAV's, dan wel bij verbindingen met relayering via tussenstations op het land of laagvliegende relaisstations, zal de vertraging in de verbinding de rechtstreekse aansturing van de UAV niet extreem bemoeilijken. De vliegeigenschappen ('handling qualities') van de UAV spelen wel een rol: slechte basiseigenschappen kunnen onder invloed van vertraging overgaan in onacceptabele vliegeigenschappen. Het heeft dus zin om op zoek te gaan naar UAV's met zo goed mogelijke vliegeigenschappen: deze UAV's verdragen hogere vertragingswaarden. Dit uiteraard vooral als de betreffende UAV direct door een operator wordt aangestuurd.
Bij gebruik van geostationaire satellieten loopt de vertraging doorgaans zover op dat de UAV-operator, ondanks alle compensatietechnieken die beschikbaar zijn, vooral in een supervisierol (programmeren en bewaken van de route) zal opereren. Alleen de

sensoren van de UAV, die een iets minder kritische rol vervullen, zullen ook in dit geval meestal nog rechtstreeks door een operator aangestuurd kunnen worden.

Summary

Purpose:
UAV's (Unmanned Aerial Vehicles) are remotely controlled from a GCS (Ground Control Station). The nature of the connection between the two is such that some delay of the control signals from GCS to UAV and of feedback (telemetry and sensor information) is to be expected. These delays may have an impact on the performance of the UAV operator.

The Royal Netherlands Air Force (RNLAF) is considering the potential acquisition of UAVs. In this process it is of importance to know the kind of constraints that arise from delays resulting from the various possible ways of UAV operations, and the potential solutions that may be applied in a candidate for acquisition. TNO performed a study specifically aimed at signal latency. Other aspects of the data link (e.g., bandwidth, continuity of the transmission, noise and trustworthiness) were not part of the commission.

Method:
We examined literature on sources of delay (and performed some calculations in this area). Additionally, we studied literature concerning the effects of delays on human performance, and literature on potential solutions for the delay problem.

Results:
Depending on the situation, delays turn out in the range of 100 to 1600 ms (and even more). This is a considerable amount given that 100 ms delay usually leads to measurable degradation of human performance. Delays of about 250-300 ms quite often lead to unacceptable airplane handling qualities. Techniques such as filtering and predictive displays exist that may extend the range of acceptable delays up to about 400 ms or more. This holds for the UAV control. Control of UAV sensors is considerably less critical and the use of the delay compensation techniques will probably lead to acceptable performance with delays up to 1000 ms and beyond.

Conclusions:
Signal delays between GCS and UAV will not significantly impede direct control of the UAV in the case of line-of-sight connections or while using relay stations on or close to the earth. Handling qualities of the UAV play a role: poor handling qualities of the UAV may transform into unacceptable handling qualities under the influence of delays. Therefore, it is useful to look for UAVs with good handling qualities: They can withstand higher delays. This is of interest first and foremost if the UAV in question is directly controlled by a human operator.
When geostationary satellites are used, delays will generally be so high that a UAV operator, all the compensation methods notwithstanding, will just operate in a supervisory role (programming and overseeing the route). Only the control of the sensors of the UAV, less critical than the control of the vehicle, may be handled directly by an operator.

Contents

1 Introduction

UAV 'pilot' receives air medal

An 11th Reconnaissance Squadron unmanned aerial vehicle operator was recently awarded the Air Force Aerial Achievement Medal for safely landing a UAV after its engine seized 150 miles from the ground control station at Mostar Air Base, Bosnia-Herzegovina.
Capt. Greg Harbin was able to remotely glide the unmanned aircraft for about 30 miles, avoiding populated areas and manoeuvring the UAV to the airfield where it could be safely recovered. *The landing was made more difficult because the nose camera, used as the primary pilot camera, iced over during the descent and the aircraft was being controlled by its satellite link, which causes a delay in aircraft control response time* (Airman, 1998).

Officials release Global Hawk accident report

Air Force investigators have determined mechanical failure caused an Air Force RQ-4A Global Hawk aircraft to crash July 10 during a surveillance mission supporting Operation Enduring Freedom.
The Global Hawk, an unmanned reconnaissance aircraft, was destroyed upon impact in an unpopulated area in the U.S. Central Command area of responsibility. No one was injured in the accident. The aircraft was assigned to the 12th Expeditionary Reconnaissance Squadron, but its parent unit is the 9th Reconnaissance Wing at Beale Air Force Base, California.
According to an Air Combat Command Accident Investigation Report released Dec. 6, the primary cause of the accident was the failure of a single fuel nozzle in the high-flow position that eventually caused internal failure of the engine. *The aircraft crashed during an attempted emergency landing.* (Air Force Link, 2002)

The press stories above tell a story about mishaps with two fairly distinct Unmanned Aerial Vehicles (UAVs), the General Atomics' *Predator* and Northrop Grumman's *Global Hawk*, respectively[1]. The former is a so-called MALE (Medium Altitude Long Endurance) UAV, the latter is a HALE (High Altitude Long Endurance) UAV. Both of these UAVs have been generally very successful in the recent US military campaigns in Afghanistan and Iraq.

Apart from their dissimilar capabilities, the Predator and the Global Hawk are operated in completely different ways as well. The Predator can be controlled by a pilot just like a manned airplane using yoke and pedals, whereas the Global Hawk is almost completely automated. It is possible to override the Global Hawk's airspeed, altitude and heading, but that's about it. There is no low-level, pilot-type of control for the Global Hawk. This means that there is not much that the controller can do in case of abnormal flight conditions. The control algorithms of the Global Hawk have to be sufficiently robust to deal with unpredictable emergencies.

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[1] I assume the reader to be familiar with UAVs. For an introduction to UAVs see De Vries, Van der Veen and Krabbendam (2000).

As the above story seems to show, the human UAV controller may succeed where the autonomous UAV fails. The story also hints at the problem of control in situations with delays. It has been known for long that even small delays in control-loops may lead to large control difficulties. This problem is rather native to the UAV field because operator and UAV may be separated by large distances connected by datalinks with large latencies.

This report presents the results of a literature study on the issue of UAVs and latency. Latency is not only a problem for the control of the UAV platform itself. Most UAVs carry sensors, particularly cameras, which have to be controlled as well. This report will also deal with sensor control. Given the trend towards increasing autonomy in UAVs, camera control with delay in the loop may even be a more important issue than platform control.

Other aspects of UAV datalinks (e.g., bandwidth, continuity of the transmission, noise and trustworthiness) were not part of the commission and were therefore not studied. A study on these individual aspects or their combination may be warranted, though.

2 Sources of delay

In this section I will discuss the various sources of delays, leading to an assessment of typical delays to be expected in a few example systems. Sources of delay that will be discussed are:

- Signal transport;
- Datalink electronics;
- Encryption;
- Compression;
- Error correction;
- Synchronization;
- Computations.

2.1 Signal transport

2.1.1 Electromagnetic wave propagation

The signals involved in sending information between the UAV and the GCS are transmitted using electromagnetic waves. These waves have a finite propagation speed, which in vacuum is 2.9979×10^8 m/s. In copper and glass-fiber cables the speed is typically about 2/3 of this speed. Due to the finite speed, a delay occurs in any transmission, depending on the distance between the transmitter and receiver and the route followed by the signals.

If it were possible for the waves to crawl along the entire surface of the earth, a round-trip would take about 132 ms. Although this may seem a rather small number we will see that it is far from negligible.

Propagation of waves used for radio and TV signals (in the HF, VHF and part of the UHF band) is usually divided in three types: ground-wave propagation, sky-wave propagation and space-wave propagation.

The first category comes closest to the 'crawling' type of propagation. Mainly by means of diffraction, the waves follow the contour of the earth and manage in this way to travel beyond the visual horizon. However, due to the interaction with surface elements the signal strength gets attenuated and therefore the 'radio horizon' is, as a general rule-of-thumb, about 30 % farther than the visual horizon. An exception occurs when a temperature inversion is present (see Figure 1). In that case, the range is extended by several hundreds of kilometers, sometimes by eight times the visual range. The occurrence of this phenomenon is rather unpredictable and it is therefore not very useful operationally.

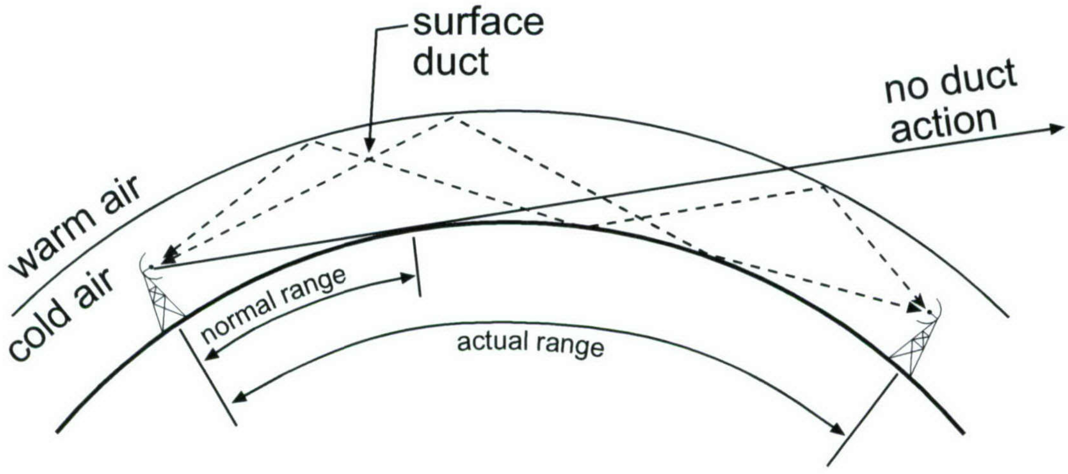


Figure 1 The effect of a temperature inversion on wave propagation.

In sky-wave propagation the signals leave the surface of the earth and are refracted by some of the layers of the ionosphere (see Figure 2). The ionosphere has at least four layers at day, the so-called D, E, F1 and F2 layers. At night, the D and E layers disappear and the F1 and F2 layers merge into one F layer. For refraction, the F layer, at 150–400 km above the earth surface, is of most importance.

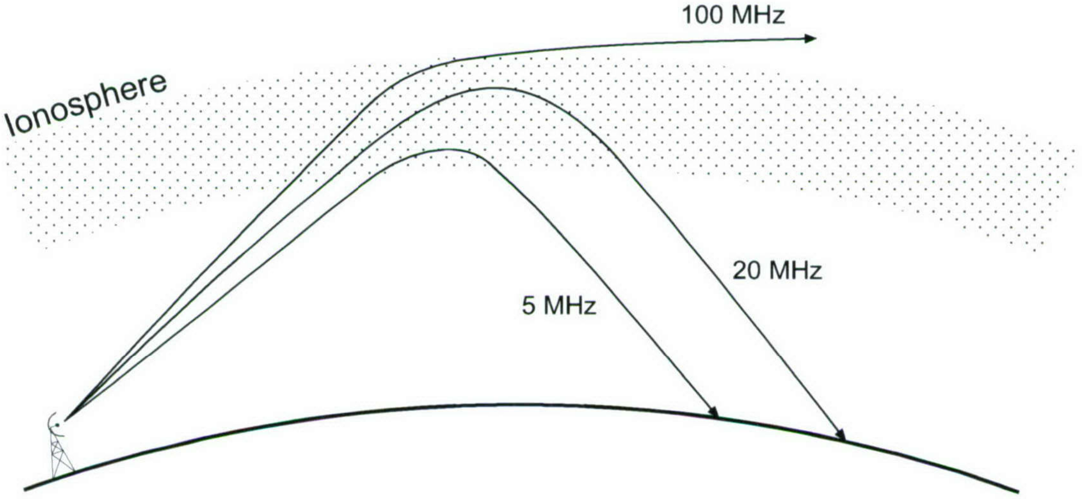


Figure 2 Refraction of electromagnetic waves by the ionosphere.

The refraction by the ionosphere depends on the frequency of the waves and on the angle of incident. Beyond a critical angle and frequency the waves are not refracted back to the earth and go spaceward (space-wave propagation).
Usually, there is a gap between the areas that can be reached by the ground waves and the sky waves (see Figure 3). These areas, called skip zones, can be hundreds of kilometers long.

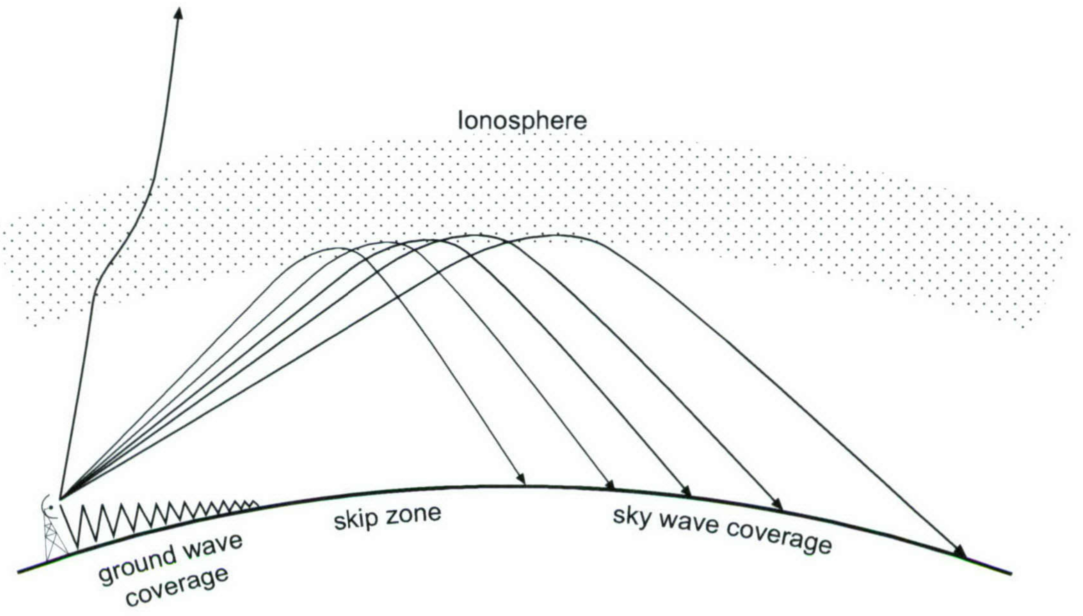


Figure 3 The origin of unreachable areas, the 'skip zones'.

Because the position and size of the skip zone varies with time of day, season and with the number of sun spots, over-the-horizon transmission without relays is not very useful for a reliable GCS-to-UAV connection. Therefore, three types of links for control of UAV and sensor are useful: line-of-sight, satellite and other relay communications. They are discussed in the following sections.

2.1.2 *Line-of-Sight links*

As discussed in the previous paragraph, line-of-sight links are limited to a range of about the visual horizon. The HF and lower VHF frequencies allow for a sometimes considerable extension of this range, but for the UHF and higher bands (L, S, C, X, Ku, Ka), wave propagation follows more or less the rules of geometrical optics, i.e. the visual horizon is roughly the upper limit.

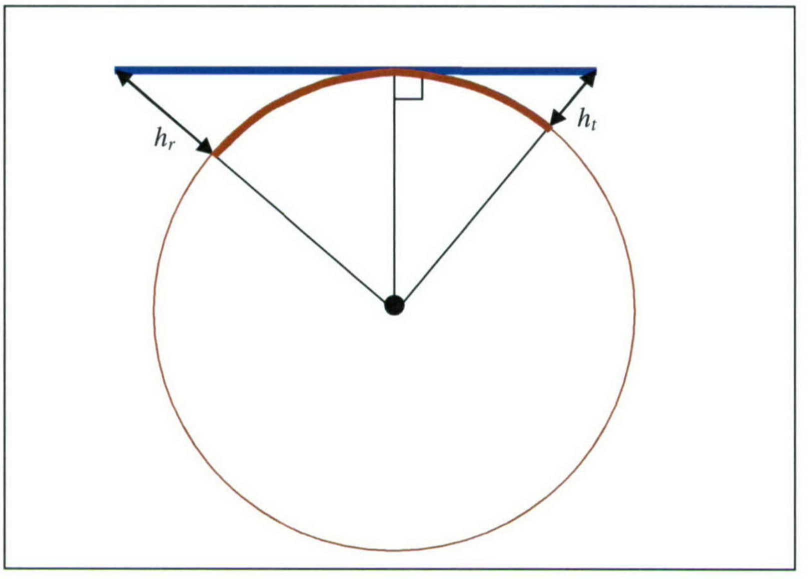


Figure 4 Distance along the surface of the earth (S) and through the atmosphere (D) between a transmitter at height h_t and a receiver at height h_r. R denotes the earth radius. Note: some authors increase the radius with a factor of 4/3 to roughly incorporate the refraction of the electro-magnetic waves by the earth's atmosphere. I have not done this here.

It is relatively straightforward to make line-of-sight calculations. Using the symbols defined in Figure 4 the distance along the earth surface between transmitter and receiver is given by:

$$S = R \cdot \left(\arccos \frac{R}{R+h_r} + \arccos \frac{R}{R+h_t} \right) \overset{h<<R}{\approx} \sqrt{2R}\left(\sqrt{h_r} + \sqrt{h_t}\right). \tag{1}$$

The distance the transmitted signals travel is given by:

$$D = \sqrt{(R+h_r)^2 - R^2} + \sqrt{(R+h_t)^2 - R^2}\ . \tag{2}$$

Using Equations 1 and 2, we can calculate some typical distance and delay values (see Table 1). It follows that line-of-sight links are rather limited in range if the UAV needs to be controlled while flying close to ground level. If the UAV operates at higher flight levels, the line-of-sight distance may increase to a more strategically sized value (see Figure 1). For all distances, even in the case of the UAV–UAV relay (last line of Table 1), the delay is low, less than 3.5 ms.
It should be noted here that the calculations assume a perfectly spherical and smooth earth, which isn't the case in real life. In mountainous areas the link range can be drastically less than shown here, due to 'shadowing' and interference.

Table 1 Maximum distances between various transmitters and receivers and time necessary for signal propagation between them.

Description	Height GCS (m)	Height UAV (m)	Earth distance (km)	Signal distance (km)	Time (ms)
Horizon average human	1.8	0	4.8	4.8	0.0
Horizon mobile mast	15	0	13.8	13.8	0.0
Horizon Vaalserberg	321	0	64.0	64.0	0.2
idem + low MALE UAV	321	900	171.1	171.1	0.6
idem + high MALE UAV	321	7500	373.2	373.4	1.2
idem + low HALE UAV	321	13500	478.6	479.2	1.6
idem + high HALE UAV	321	19500	562.1	563.1	1.9
hi HALE to hi HALE UAV	19500	19500	996.3	998.3	3.3

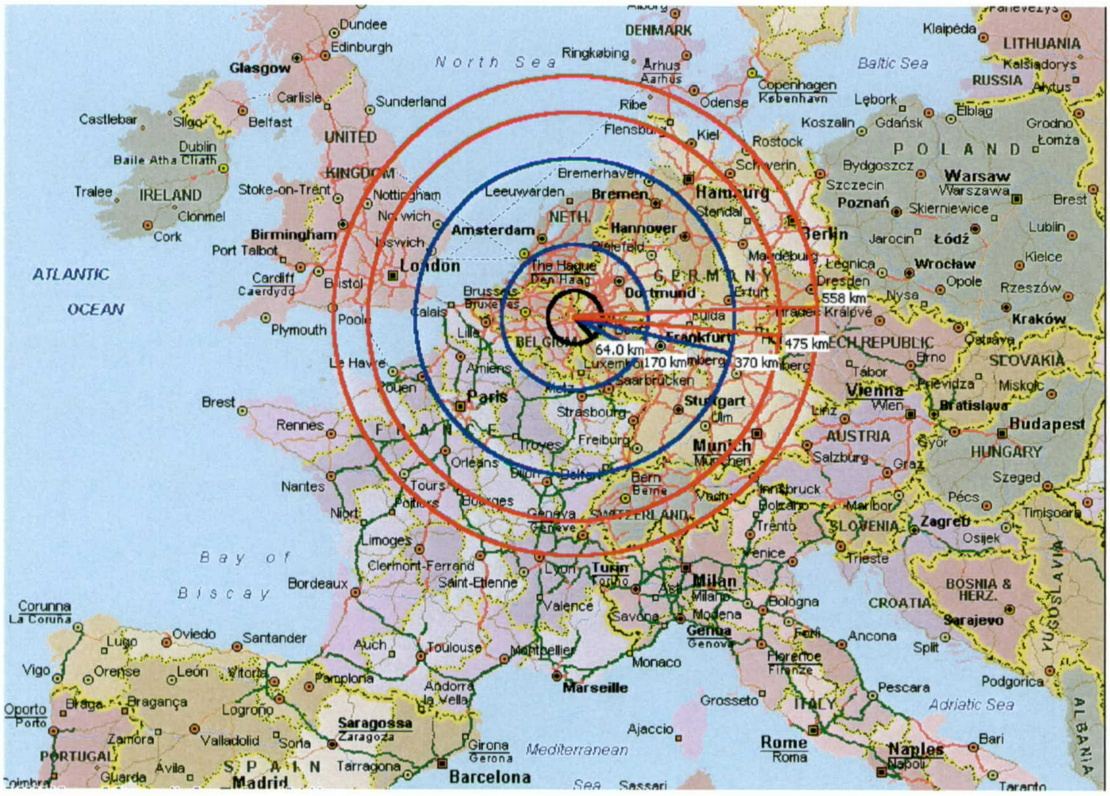


Figure 5 Line-of-sight ranges from the Vaalserberg, the highest hill in the Netherlands. **Black circle:** the horizon. **Blue circles:** mark the area in which MALE UAVs (operating height ca. 900-7500 m) are visible. **Red circles:** mark the area in which HALE UAVs (ca. 13500-19500 m) are visible. All ranges are based on a round-earth assumption without obstructions (buildings, mountains).

2.1.3 *Satellite communication*

Due to the limited range of line-of-sight datalinks, relay by communication satellite is the default alternative for over-the-horizon communication.

Using a slight modification of Equations 1 and 2 and symbols defined in Figure 6 we find:

$$S = R \cdot \left(\arccos \frac{R}{R+h_G} + 2 \cdot \arccos \frac{R}{R+h_S} + \arccos \frac{R}{R+h_U} \right), \tag{3}$$

and

$$D = \sqrt{(R+h_G)^2 - R^2} + 2 \cdot \sqrt{(R+h_S)^2 - R^2} + \sqrt{(R+h_U)^2 - R^2}\ . \tag{4}$$

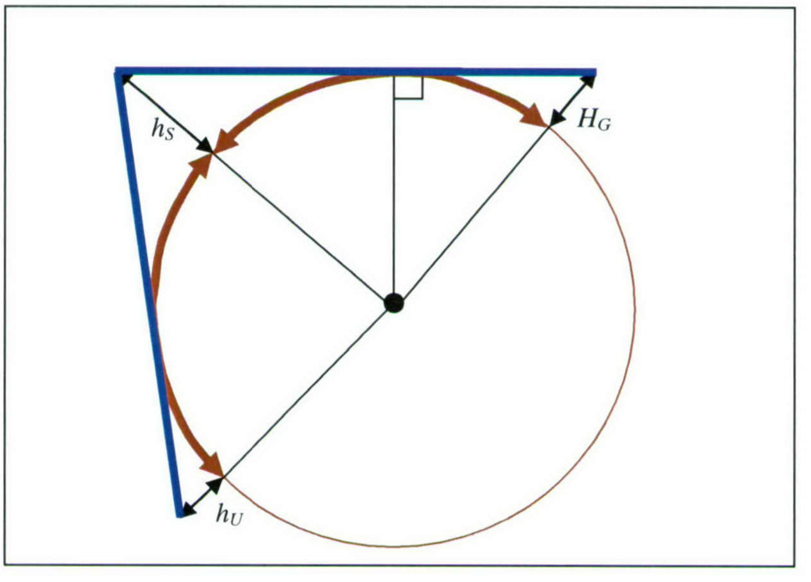


Figure 6 Distance along the surface of the earth ($S = S_{GS} + S_{SU}$) and through the atmosphere ($D = D_{GS} + G_{SU}$) between a **G**CS at height h_G , a **S**atellite at h_S ,and a **U**AV at height h_U. R denotes the earth radius.

2.1.3.1 *Low-Earth Orbit satellites*

Low-earth orbit (LEO) satellites generally orbit at a height between 200 and 800 km, usually at large angles with the equator. At these heights, a full orbit takes about 1.5 hour. As Figure 7 shows, LEOs can 'see' entire continents, but they lose sight of a given ground station in 7–13 minutes and they don't return to a given point within several hours or days (see Figure 8). LEOs can therefore not be used for sustained communication. To that end, an extensive and hence very expensive network of LEO satellites is necessary. The GPS navigation system, for instance, uses 27 satellites. The Irridium satellite telephony system was supposed to operate with 72 satellites. Calculations showed that if only 45 of those are in operation, a multiple-hop transport of a signal should have a latency of maximal 178 ms (Nichols, 1998). Simple relays using LEO satellites have a moderate signal delay between 1 and 24 ms (see Table 2).

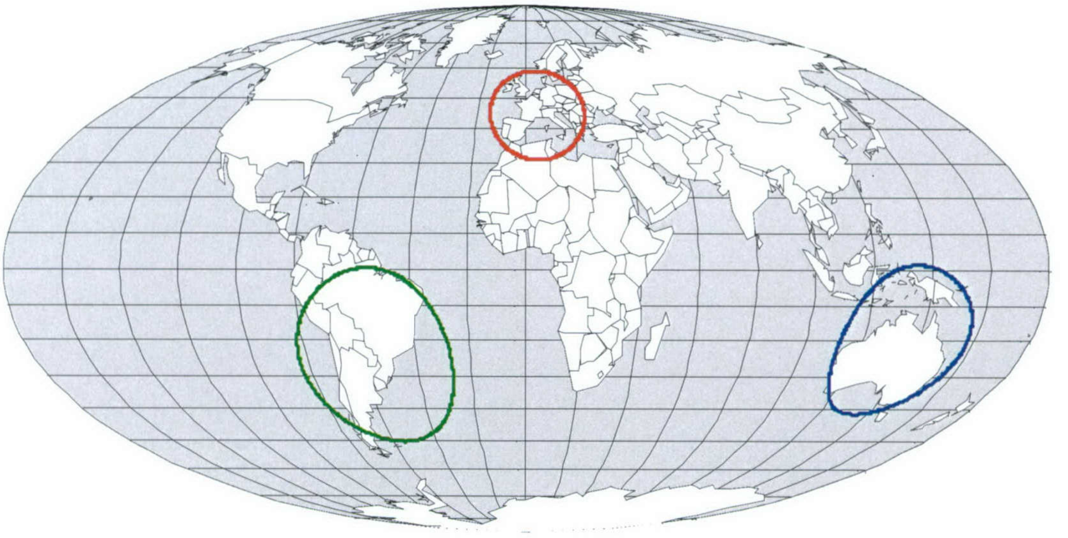


Figure 7 Visual horizon (in Mollweide projection) of a few low earth orbit satellites. Red: the KVR-1000 satellite at 200 km. Green: the SIS satellite at 470 km. Blue: the EarlyBird satellite at 680 km.

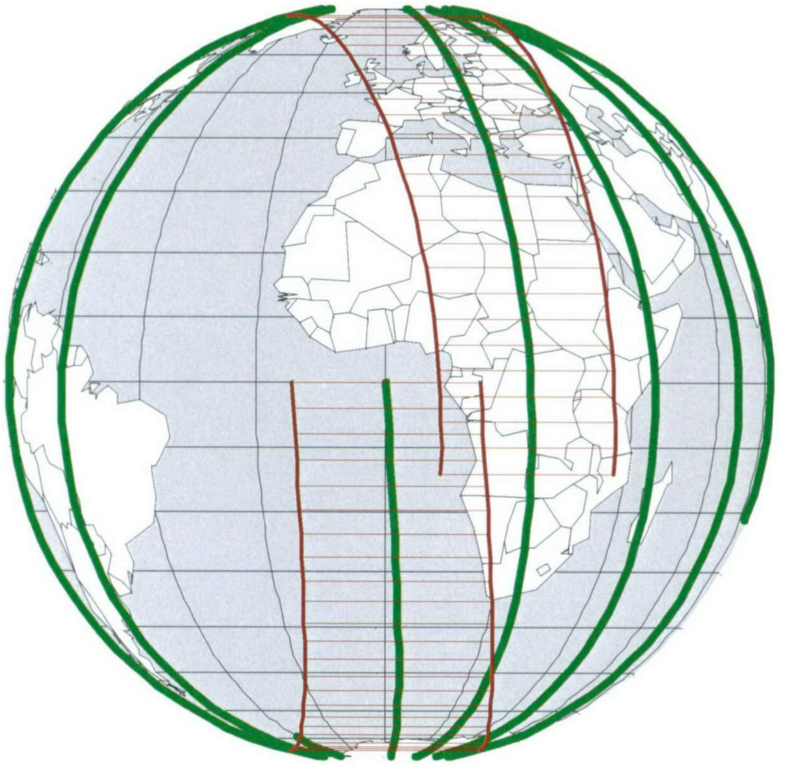


Figure 8 A low-earth orbit satellite in a polar orbit at a height of 200 km (orthographic projection). The green curve marks the positions above which the satellite flew in a time span of 9.3 hours. The area hatched in red gives an indication of the area covered during the trip and the amount of overlap between successive laps. Each of the horizontal lines indicates the longitudinal view. Horizontal lines are separated in time by one minute.

Table 2 Distances and delay times involved in low-earth orbit satellite relay calculated using Equations 3 and 4. All rows except the last contain various GCS-UAV configurations. The last row describes a UAV-satellite-UAV link.

Satellite height (km)	Height GCS (m)	Height UAV (m)	Min. dist. (km)	Max. dist. (km)	Min. time (ms)	Max. time (ms)
200	15	100	399.9	3269.1	1.3	10.9
470	15	100	939.9	5036.2	3.1	16.8
680	15	100	1359.9	6095.1	4.5	20.3
680 + low MALE UAV	15	900	1359.1	6166.5	4.5	20.6
680 + high MALE UAV	15	7500	1352.5	6368.8	4.5	21.2
680 + low HALE UAV	15	13500	1346.5	6474.6	4.5	21.6
680 + high HALE UAV	15	19500	1340.5	6558.5	4.5	21.9
680 + hi HALE to hi HALE	19500	19500	1321.0	7043.8	4.4	23.5

2.1.3.2 *Geostationary satellites*

Most of the current over-the-horizon UAV operations are handled with geostationary satellites. Geostationary satellites are, as their name suggests, stationary with respect to the earth. Because the earth is rotating, geostationary satellites must have a circular orbit lying in a plane through the equator. The radius of the orbit is about 42,147 km, which is 35,768 km above mean sea level.

Due to their altitude, geostationary satellites can cover large parts of the earth (see Figure 9). Only the polar areas escape attention. A GCS and a UAV that are within the same service area can, at least in principle, receive each other using the satellite as relay. Of course, at the boundaries of their ranges signal reception gets considerable worse due to the oblique incident angle and the longer pathway through the atmosphere. Also note that wide area beams used by the satellites often cover only about 20% of the total possible area. If a satellite uses spot beams, the area covered will be considerably smaller. Generally, more than three geostationary satellites will be necessary to cover the whole earth.

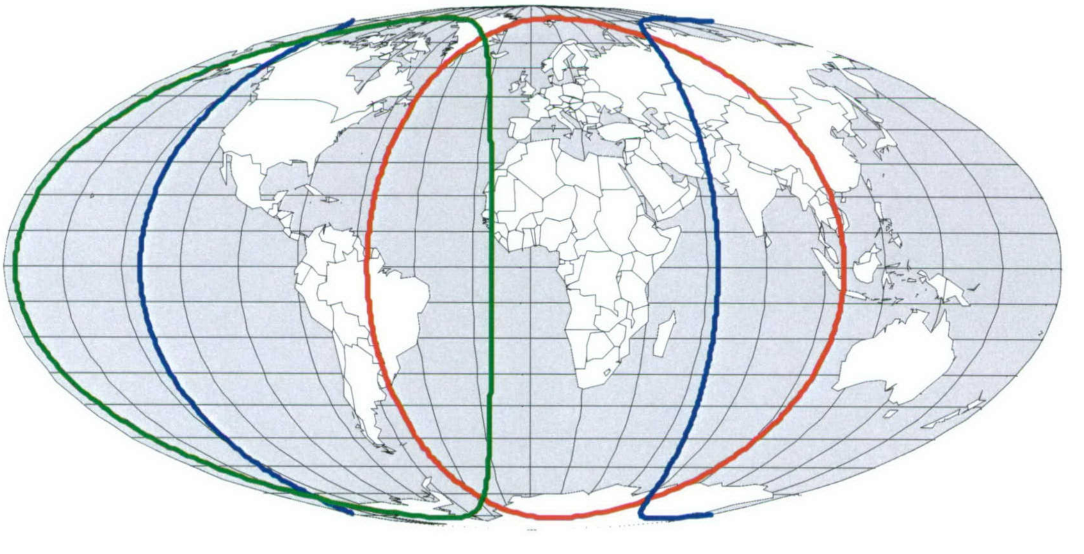


Figure 9 The surfaces 'seen' by three geostationary satellites positioned at 25° W (red), 145° W (blue, split in two parts) and 85° E (green). The earth and the marked areas are in Mollweide projection.

Table 3 Signal travel distances and times calculated using Equations 3 and 4. Minimum distances occur when GCS and UAV are both straight below the satellite. Maximum distances occur as sketched in Figure 6. Round-trip delays are obtained by doubling the indicated times. The values here and in some other tables are expressly shown with an absurd number of digits to highlight the minimal differences between them.

Description	Height GCS (m)	Height UAV (m)	Min. dist. (km)	Max. dist (km)	Min. time (ms)	Max. time (ms)
Mobile mast	15	0	71536.0	83335.9	238.6	278.0
Hill	321	0	71535.7	83386.1	238.6	278.1
idem + low MALE UAV	321	900	71534.8	83493.2	238.6	278.5
idem + high MALE UAV	321	7500	71528.2	83695.5	238.6	279.2
idem + low HALE UAV	321	13500	71522.2	83801.3	238.6	279.5
idem + high HALE UAV	321	19500	71516.2	83885.2	238.6	279.8

2.1.4 *Relay*

2.1.4.1 *Fixed repeaters*

For civilian over-the-horizon communication the signals are often relayed by means of one or more fixed relay stations. The transport delays caused by this method are very low (about 1 ms for every 300 km). However, due to their stationary nature, these relay stations are not of much practical use for military operations, since the opponents are not likely to provide the necessary facilities. It may be used to connect MOB, AOB, FOB and HQ in more friendly areas, though.

2.1.4.2 *Pseudolytes*

Pseudolytes are self-propelled flying platforms that serve in the same role as satellites, albeit at a considerable lower altitude (typically 60,000 feet) and with less endurance than either low-earth orbit or geostationary satellites.

Figure 10 The AeroVironment *Helios* taking off from the Pacific Missile Range Facility, Kauai, Hawaii.

The role of UAVs as pseudolytes is still in a concept phase. As a follow-up to the NASA Pathfinder prototypes, the solar-powered *Helios* (see Figure 10) built by AeroVironment is planned to have an endurance of six months while flying at an altitude of 60,000–100,000 feet. Among other uses, it is advertised as a communications platform.

Other R&D groups are adapting existing UAVs to their needs. In their *Extendor* program, QinetiQ (the commercial branch of the former UK defense research laboratory DERA) is exploring the possibilities of UAV relays using a Predator UAV. In an experiment, the modified Predator successfully relayed digital messages from a Forward Air Controller to a Jaguar HUD. The UAV also relayed video to a F-16 and F-14 (Hardy, 2002).

Given its endurance and operating height, the Predator (24-30 hours, 45,000 ft) seems a less likely candidate for communication relay than the Global Hawk (40 hours, 65,000 ft). The Helios has a larger endurance than the other systems, but doesn't have, at this time, sufficient payload capacity and electrical power to carry a large communication relay platform.

At the planned heights (up to 100,000 ft), UAV relays yield a maximum range of approximately 1300 km. The one-way signal delay caused by this distance is 4.3 ms. If the platform lives up to its promise this low value would make it an ideal relay station for commanding UAVs. It can loiter above a fixed position on earth like the geostationary satellites, but it can be easily maneuvered to other areas when the need arises.

2.2 Datalink electronics

The analog electronics that build up the datalink introduce a certain amount of latency. One source (Hall, Hart, & Wasel, 2001) claims that most current UAV systems utilize an analog datalink that causes a minimal latency of about 100 ms, whereas legacy RF links used to have a latency of 40 ms. They warn that modern digital links will have higher latencies than their analog counterparts.

Quite often, there are various steps between the UAV and its GCS. For instance, with the French Sperwer UAV-system, in use with the Dutch army's 101st Remotely Piloted Vehicles Battery, the signals from the GCS are sent by glass-fiber cable to a Ground Data Terminal (GDT), which transmits them to the UAV (see Figure 11). The rational is that the GDT works like an electromagnetic beacon, making it vulnerable to attack. Therefore, it is better to separate the two functions of control and communication by a considerable distance.

It is safe to assume that every extra datalink that gets in between the GCS and the UAV adds its own latency. Hence, communications systems built like the Sperwer will have electronics related latencies of at least 200 ms.

Figure 11 Top: an overview of a typical Sperwer battery configuration. Bottom left: the interior of the Sperwer GCS. Bottom right: The Sperwer GDT.

2.3 Encryption/Decryption

Signals from and to the UAV should be encrypted if a datalink is used that is easily detected and compromised such as the UHF-band, which generally doesn't require directional antennas. The usage of narrow beams and frequency hopping schemes increases security. Encryption will nevertheless be necessary to increase security and to provide authorization of control (by means of authentication).

Luckily, encryption does not add much to the datalink's latency. Blaze (1996) encrypted high bandwidth links using a Pentium 90 MHz computer with a latency of about 20 ms. Nowadays computers or dedicated hardware should be able to improve on

this by an order of magnitude. One can expect a 1–2 ms delay. However, each link (up and down) needs both encryption and decryption. Therefore, roundtrip latency due to encryption will probably be in the order of 4–8 ms.

2.4 Compression/decompression

Conservation of bandwidth is of great importance. The radio spectrum is a scarce resource and most of the available frequency bands are already in use, regulated by multi-national treaties and organizations (see, e.g., FCC, 2002). Given the successful use of UAVs in the Balkan, Afghan, and Iraqi theatres and the plans to convert 1/3 of the US deep-strike force into unmanned platforms (US Senate budget proposal 2000), it is clear that the number of datalinks will increase. The military has to conserve its allotted space and hence must turn to data compression and other bandwidth-saving techniques.

In the UAV case, probably only the high bandwidth downlink will need to be compressed (video and radar data). The uplink, consisting mostly of low data-rate control commands does not need this. In this section we will concentrate on the compression of video-material.

There are many different video compression methods. The compression of choice at the moment is MPEG-2 which will be succeeded by MPEG-4 shortly.

MPEG is a 'lossy' compression method, which means that the original and the compressed and decompressed version of the original are not the same. The difference may or may not be noticeable, depending on the quality setting. MPEG is akin to the JPEG standard for still imagery, but it not only exploits redundancy within a single movie frame but it also uses redundancy between several successive frames. In order to do this, MPEG has to buffer several video frames, which means that without performing any calculations at least 100 ms or so are already lost.

MPEG-2 uses JPEG-like coding for so-called I-frames, and can additionally calculate P-frames (forward **P**redicted frames, based on previous I and or P frames) and B-frames (**B**i-directional interpolated frames, based on previous and future I and P frames) to decrease data rate and/or to improve quality. Chow (2005) claims compression latencies to be 200 ms to 400 ms, 200 ms to 500 ms, and 400 ms to 850 ms for movies with I-frames, IP-frames, and IBP-frames, respectively.

Minerva Networks (2001) produces a hardware MPEG-compressor for video-conferencing applications. They claim a 'record breaking end-to-end latency' of 150 ms. Given that they don't use full resolution video one should scale-up their value by a factor of about 2.5 to obtain a latency value for full-screen video. This amounts to about 375 ms. MPEG compression is generally much more time-consuming than MPEG *de*compression, hence this end-to-end value (compression plus decompression) is close to Chow's range of values. We will use this value for our estimates.

2.5 Error correction

Error correction is necessary to prevent the potentially disastrous situation of distorted control commands being executed by the UAV.

In the TCP/IP protocol used for Internet communications, checksums are applied to detect data corruption. When a data packet is received corrupt, a retransmission is requested. Of course, this implies a relatively enormous amount of latency.

Other protocols, like UDP/IP, simply drop the corrupted packet. This is generally no problem for data that is not essential, like a couple of frames from a video or sound transmission, but for control signals this is probably not a good idea. In this case error correction is necessary.

By means of clever encoding it is often possible to detect data corruption and correct for it. A certain amount of extra data (depending on the amount of errors one would like to be able to correct) needs to be send along with the data. Hardware solutions exist that have a latency of less than 1.5 ms (see, e.g., 4i2i communications Ltd, 2001).

2.6 Synchronization

In a process consisting of several sequential free-running sub-processes the lack of synchronization is a potential source of delays. When two processes are not synchronized but take about the same time, the second process has to wait for the first process to finish. In a worst case scenario this idle waiting can take as much as the total process cycle time of the first process. On average, half the processing time will be spent waiting.

It is hard to tell in which of the stages of downlink and uplink unsynchronized processes appear. It is at least very likely that the image sensor and the monitor its image is displayed on are unsynchronized. Given a refresh rate of 60 Hz this implies an average delay of 8 ms. It is very likely that more synchronization delays will be present.

2.7 Computation delays

The presentation of the Human-Computer Interface (HCI) of the UAV operator takes some time. Symbology has to be updated, sensor footprints need to be calculated, maps have to be moved and/or rotated, and the operator's input has to be processed.

In a UAV control concept like that of the Tactical Control Station (TCS, see NSWC, 1999) a hardware abstraction layer shields the operator from the specifics of the hardware he is controlling. The purpose of this is to increase interoperability. In the future, TCS operators should be able to control various kinds of UAVs from the same console. The abstraction layer converts outgoing data from the generic console to commands specific to the UAV, and does the same for the incoming telemetry and sensor data. This layering will add to the delay.

It is hard to give any hard figures for the delays caused by all this. The latency will decrease with increasing computing power and is probably in the order of 10–30 ms at this time.

2.8 Total signal delay

We are now ready to calculate an overall latency. In Table 4, latencies are summarized for two configurations, a short-range line-of-sight connection and an over-the-horizon connection using geostationary satellites as a communications relay. It is a 'minimax' approach, which means that we estimate the worst case using the lowest possible delays. It is quite possible that sub-optimal hardware and software results in higher latencies than presented here.

The largest estimate is 1672 ms. This may sound rather high, but it may actually be an underestimation. For instance, there are claims that England-based Dutch UAV operators who were controlling a camera of a Predator UAV flying above Bosnia experienced delays of up to 6 s (Müller, 2001). It is hard to determine how precise this estimate is, but it is clear that our estimate of about 2 s is in the right ballpark and certainly not too high.

Table 4 Estimates for minimum and maximum latencies (in ms) for two types of datalinks: line-of-sight (LOS) and geostationary satellite relay (GEO). In the minimum configuration we assume no encryption, compression and error correction and use the lowest estimation of electronics latency. In the maximum configuration we take all factors into account and assume the presence of a GDT and use a higher estimation of electronics latency. We also assume that only the downlink is compressed. Although these numbers appear to be rather precise it is better to regard them as rough estimates. The number of digits has been increased to make the small contributions to the total delay visible.

	GCS-UAV configuration			
	LOS		GEO	
	min	max	min	max
Tranceive	40.0	300.0	80.0	300.0
Transport	0.2	3.3	239.0	281.0
Encryption	0.0	4.0	0.0	4.0
Compression	0.0	375.0	0.0	375.0
Error correction	0.0	1.5	0.0	1.5
Synchronization	8.0	32.0	8.0	32.0
Computations	10.0	30.0	10.0	30.0
Uplink	58.2	370.8	337.0	648.5
Downlink	58.2	745.8	337.0	1023.5
Round trip total	116.4	1116.6	674.0	1672.0

3 Control of time-delay systems

Anyone who has ever tried to take a shower in a house with a long distance between shower and heater knows that it is very hard to get the temperature of the shower just right. Due to the large delay between adjustment of the shower faucets and the corresponding change in water temperature it takes a lot of experimenting and overshoots (too hot or too cold) before a comfortable temperature has been finally set.

Humans are notoriously bad in dealing with systems containing delays. Therefore, delays have been a popular topic for research. Ricard (1994) writes in his extensive bibliography on manual controls with delays: "For experimentalists, delay of visual feedback has served as a reliable cue over the past four decades for, in the limit, lagging a system's output can always be expected to effect human control performance."

In this section, a short introduction to the theory of control of delayed systems will be presented. This will be followed by some general psychophysical data on delayed control and data from the more relevant world of airplanes and simulators.

3.1 Theory

A human UAV controller can be seen as a comparator who compares desired system output with the actual system output and reacts on the difference. Of course, this is an absurd oversimplification[2], but it is useful to show the source of the control problem.

In Figure 12 such a simplified UAV operator can be seen. At t = 0, a controlled parameter, e.g. speed or altitude of the UAV, needs to change from one level to another level. This is symbolized by the 'step' box in the diagram. The UAV operator compares this desired level with the actual, delayed system state and uses the difference of these levels to control the system state. The difference signal multiplied by a gain factor feeds directly into the controlled system, which, in this case, is modeled by a simple integrator. The lower part of the figure shows the responses for various values of the operator gain. A low gain leads to a slow response; however, it reaches the desired level in a very stable manner. Higher gains will bring the system quicker in the desired range, but they tend to overshoot the goal level followed by (dampened) oscillations. Beyond a certain critical gain the system becomes unstable. Corrections and errors get into counter phase and amplify each other.

The type of oscillations and the critical value of the gain are of course totally dependent on the specifics of the system (vehicle transfer function and delay). Many textbooks on control theory deal with this and we won't go into details here. The example was used here to make it plausible that any controller, human or machine, will have problems handling delays and that the handling problems are not the result of a specific human shortcoming.

[2] For a more in-depth discussion of human controller models, see (Hess, 1997).

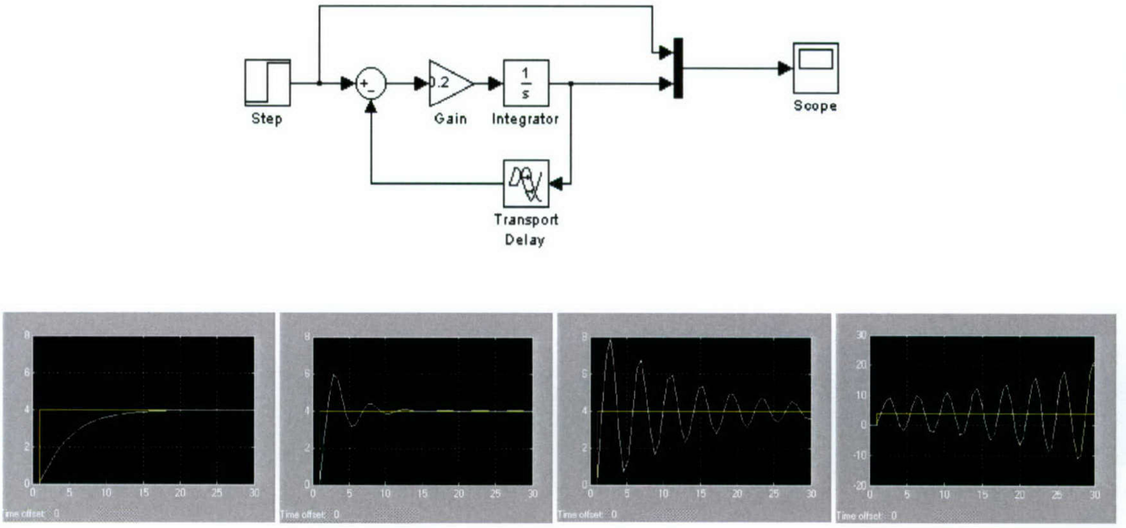


Figure 12 Above: a Matlab SimuLink model of a simple controller-vehicle-delay loop. Below: Output of the model for various values of operator gain. The higher the gain gets, the less stable the system. In the last panel, a value of gain is reached where the system becomes unstable.

3.2 Equivalent or effective platform delay

Apart from the straightforward time delay caused by finite signal transport speed, other types of delays are also distinguished (Smith & Sarrafian, 1986):

> To a pilot, time delay is the dead time between his force input to the stick and the beginning of any aircraft response or output. This delay can come from a variety of sources within the flight control system.
>
> A system that reproduces the exact shape of an input after an interval of dead time is defined as exhibiting transport, or pure, time delay.
>
> ...the majority of time delay in modern electronic flight control applications is not caused by pure time delays. Typically the complexity of modern control system design strategies results in cascading numerous dynamic elements which can introduce a perceived delay in the initial response of the aircraft to a pilot input. This form of time delay is often referred to as "**equivalent**" or "**effective**" time delay, depending on the measurement method. Each method represents an approximation of the dead time sensed by the pilot.

3.3 Psychophysical data not directly related to airplane control

From the huge body on general effects of time delay on human performance only a few examples will be presented in this section. For an extensive bibliography list, see Ricard (1994).

As Ricard said, you are sure to find effects from delays. However, the size of the effects varies wildly in the literature. Wargo (1967) studied controller performance using pursuit tracking displays (displays that both show the value to be achieved by the controller and the actual value) versus compensatory displays (displays that only show the error, i.e. the difference between the required and the actual value). Pursuit tracking displays have a better performance than compensatory displays. However, pursuit

tracking displays are more influenced by delays than compensatory displays, a result also found by Conklin (Conklin, 1957; Conklin, 1960). In a simple tracking task, a delay of 200 ms lead to a degradation of 5% of the performance for pursuit displays whereas compensatory displays were only degraded by 2 %. At 840 ms these numbers were 30 and 20%, respectively.

The size of this effect does not differ much from the one reported by Hill (1976) in an entirely different experiment. He examined the control of a manipulator arm, a slave, by a master arm operated by a human controller. The results show that the time needed for execution of several manipulation tasks grows linearly with transmission delay. Hill also noted the occurrence of a 'move-and-wait' strategy. With longer delays controllers often wait for the slave arm to reach a certain position before they go on to give the next motion command. After about 300 ms the percentage of the time the arm is busy moving starts to decay considerably, from about 50% for no delay and 45% at 300 ms delay up to 10% for 10 s delay.

The above mentioned authors reported relatively small effects for delays in the hundreds of milliseconds. On the other hand, Smith and Bowen (1980) found that 66 ms delay already leads to measurable eye-hand coordination deterioration. Subjects typically can adapt to delays lower than 100 ms. Other researchers report stronger effects of delays as well. For instance, Foulkes and Miall (2000) data on a simple 2D tracking task show subjects to have errors two and three times as large for delays of 200 and 300 ms, respectively, compared to the errors in the non-delayed condition.

3.4 Airplane-related data

The military standard MIL-F 8785 (US Department of Defence, 1980) sets some rules on acceptable delays. It defines three levels of flying qualities (p. 4):

Level 1: Flying qualities clearly adequate for the mission Flight Phase

Level 2: Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists

Level 3: Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A Flight Phases can be terminated safely, and Category B and C Flight Phases can be completed.

The flight phase categories A, B, and C mentioned in Level 3 are defined as (p. 2-3):

Category A: Those non-terminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight-path control. Included in this category are
a. Air-to-air combat;
b. Ground attack;
c. Aerial recovery;
d. Reconnaissance;
e. In-flight refueling (receiver);
f. Terrain following;
g. Antisubmarine search;
h. Close formation flying.

Category B: Those non-terminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Included in this category are:

a. Climb;
b. Cruise;
c. Loiter;
d. In-flight refueling (tanker);
e. Descent;
f. Emergency descent;
g. Emergency deceleration;
h. Aerial delivery.

Category C: Terminal Flight Phases are normally accomplished using gradual maneuvers and usually require accurate flight-path control. Included in this category are:

a. Takeoff;
b. Catapult takeoff;
c. Approach;
d. Wave-off/go-around;
e. Landing.

For an airplane to be classified as having a certain level of handling qualities, a maximum allowable delay is specified for each level (p.42):

Level	Allowable delay (ms)
1	100
2	200
3	250

Clearly, given the description of level 3 above, 250 ms is the absolute maximum allowable delay, typical for very poor handling qualities.

Berry (1985) examined the effects of delays added to the lateral (roll) and longitudinal (pitch) stability augmentation system (SAS) of the NASA-modified F-8 jet for landing and formation flying tasks. They examined effects of adding between 20 and 200 ms of delay to a system with an inherent delay of 130 ms using a Cooper-Harper flying qualities rating scale (see Figure 13). In the pitch axis, in calm air, spot landings were most strongly influenced by time delay. In the roll axis, in calm air, formation flying was most strongly influenced by time delay (Cooper-Harper ratings increased from an average of about 3 to 6 if the incremental time delay increased to 140 ms). However, when landings were made in turbulence, flying qualities in pitch were only slightly degraded, whereas in roll they were severely degraded (ratings increase from 3 to 8 instead of from 3 to about 4 when landing in turbulence instead of in calm air). Berry found the MIL-F-8785 specification to be reasonable for lateral time delays, but a bit too stringent for lateral time delays.

Smith and Sarrafian (1986) counter the rigid rules of the MIL-F-8785 specification. In their research they found acceptable flying qualities to be strongly dependent on the specific task (approach, landing). In the fly-by-wire NASA F-8 project, an equivalent latency of 220 ms yielded a pilot rating of 4 for low stress tasks and 8 for high stress tasks on a Cooper-Harper flying qualities scale. They found that for planes with an equal amount of total *equivalent* delay (see Section 3.2), where one has a slow feel

system (force feedback on the control stick) and the other a fast feel system each with its own characteristic equivalent delay, the one with the slow feel system has the best pilot rating. Because the total amount of delay is the same in both cases, the amount of pure delay in the fast system is the largest. The rating seems to be determined by this pure delay only. Smith and Sarrafian therefore question the maximum delay values set in the military standard MIL-F-8785C, because it doesn't make this distinction.

However, David, Bimal and David (1992) also found that feel system equivalent delay differs from pure transport delay, but that there are also correlations. They thought it too early to discount the contribution of the feel system's equivalent delay from the required maximum set by MIL-F-8785C.

In a one-dimensional tracking task, Hess (1984) showed that vehicle dynamics can have a dramatic effect upon airplane-pilot coupling especially when time delays are present. He used simple gain, first and second order dynamics. Subjects couldn't complete the task with the latter dynamics and a delay of 357 ms. At a delay of 214 ms performance has deteriorated somewhat, but not dramatically. What did change was the ability of the closed-loop pilot-vehicle response to abrupt, transient inputs.

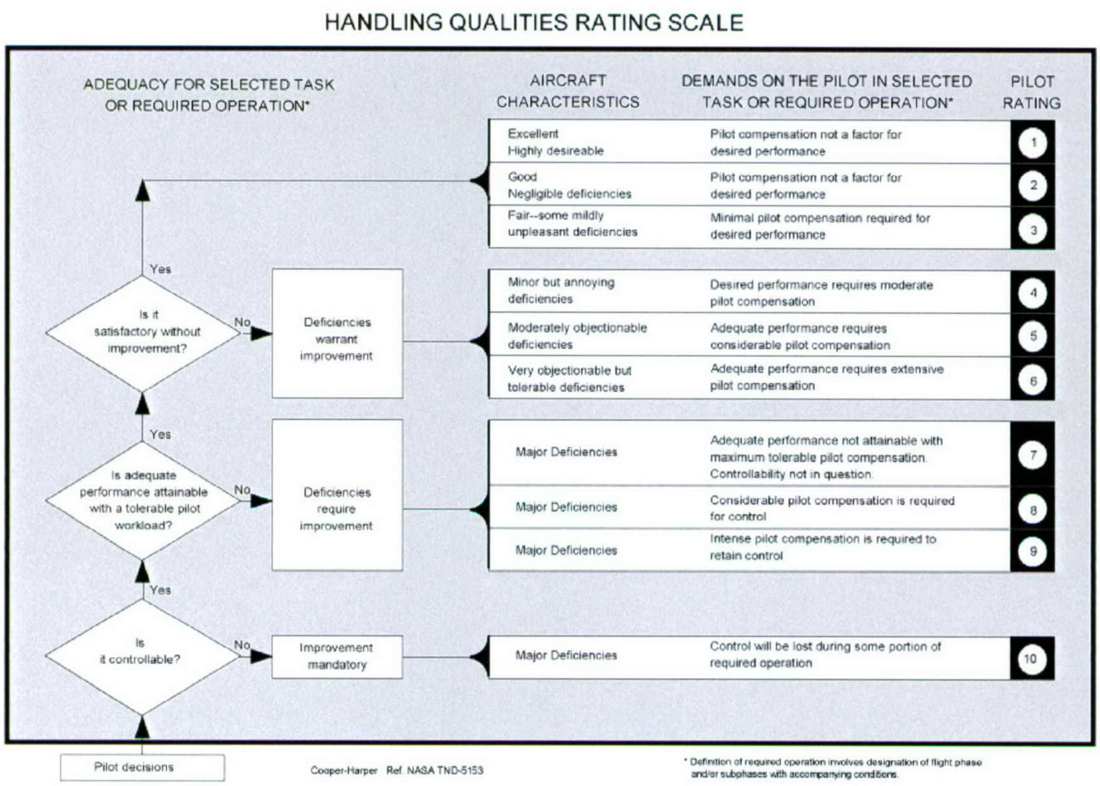


Figure 13 Example of a Cooper-Harper handling qualities rating chart.

3.5 Simulators

Delays have always been an issue in flight simulators. Not only do they deteriorate the performance of the pilot, but also quite often lead to simulator sickness or at least to various unpleasant feelings. Research in simulators often focuses on delays in the computer generated graphics and/or the motion system, which is not quite the same as

the delays to and from the controlled vehicle in the UAV case, but has comparable effects, and is for most means and purposes indistinguishable by the operator from control delay (Crane, 1983).

Frank, Casali and Wierwille (1988) examined the effects of both visual and motion delays. Both delays contribute to performance degradation and uneasiness, but delays in visuals more than delays in motion. Performance deteriorates in proportion to amount of delay; both components contribute. Uneasiness reaches a peak around 300 ms.

On the other hand, Draper, Viire, Furness and Gawron (2001) did not find an effect of extra delay on sickness. A comparison across experiments suggested no appreciable increase in simulator sickness with increasing extra time delays (125 and 250 ms) above the nominal value (48 ms).

Whiteley and Lusk (1990) examined landing performance under conditions with delay. Landing performance with a 90 ms delay was better than 200 ms delay. In a sidestep maneuver scenario they found significant differences in roll and heading control for 90, 200 and 300 ms delay, but no significant difference in crashes. They reported more control stick activity with increasing delay.

Gawron, Bailey, Knotts and McMillan (1989) examined the effects of pure transport delay added to the pitch and roll flight control system on pilot performance using the NASA variable-stability NT-33A aircraft. They compared the results with those of a fixed-based flight simulator. Generally, they found that the effects of the delays were more severe for a simulated F-16 (fighter) airplane than a C-141 (transporter) airplane. For the F-16, roll errors started to increase after about 40 ms, increasing almost twice as fast in the simulator than in the real airplane adding 17% and 11% to their respective baseline errors for each 100 ms of additional delay. Pitch errors started to increase after about 30 ms adding 17% and 25% to their respective baseline errors for each 100 ms of additional delay. For the C-141, roll errors started to increase after about 60 and 110 ms for the simulated and real airplane, respectively, adding 13% and 19% to their respective baseline errors for each 100 ms of additional delay. Pitch errors started to increase after about 50 and 90 ms for the simulated and real airplane, respectively, adding 17% and 25% to their respective baseline errors for each 100 ms of additional delay. In short: for slow airplanes longer delays are tolerable and in simulators (without motion feedback) performance starts to deteriorate earlier than in the real airplane (with motion feedback).

Bailey, Knotts, Horowitz and McMillan (1987) measured degradation in ground-based simulation versus in-flight simulation using a Cooper-Harper rating scale. They found a one C-H rating unit decrease for 100 ms delay in ground-based simulation and 1.5 unit for in-flight simulation. Degradation starts at about 130 ms of added delay (with a 100 ms baseline), though the authors mention in their conclusions a number of 50 ms (+100 ms baseline) as an acceptable delay. In the study, pilots developed different control strategies to handle delays. Some pilots used low gain control; others used high frequency pulsing type input, and some tightened their grip on the controls.

Miller and Riley (1977) examined visual delays and compared moving base and fixed-base simulators. They found that 'bad' planes (with a low C-H rating of 6) allow for only 47 (baseline) + 31 ms (additive) delay. With good ones (with a C-H rating of 3.5), a 47 + 3*31 = 150 ms could be handled. They stated that in the case of bad planes no

added delay is actually possible. The effect of the motion base was significant even at 0 delay. For a basic plane the effect was found in the fixed base after120 ms delay, and in the moving base after 240 ms. The numbers for a good plane were 120-240 ms and 360 ms, respectively. At high workloads, lower delays were found to be acceptable.

The DIS (Distributed Interactive Simulation) standard specifies a maximum end-to-end latency, i.e. time from onset of an action to a corresponding change in the simulator's output, of less than 300 ms for 'loosely coupled' interactions and less than 100 ms for 'tightly coupled' interactions, e.g. formation flying. DIS works by sending various data packages over a simulation network. A position package is used to update position, velocity and acceleration. While waiting for the next packages to arrive DIS uses the entities' 'dead-reckoned' position. This is an extrapolated position estimated based on a simple motion calculation using known velocity and acceleration (the latter is not obligatory). The dead-reckoning process is meant to deal with both low update rates and latencies. In two experiments, De Vries (1999) and De Vries & Kappé (1999) examined the effect of delay in a DIS-like simulation in which two vehicle controllers had to minimize steering errors with respect to their own vehicle paths and were required to line-up their respective vehicles. The experiments simulated both internal delays (delays within the vehicle's own simulator loop) and external delays (transport delays between simulators). In both experiments, line-up errors depended more strongly on the internal delay than on the external delay. The contribution of the internal delay to the line-up error was 2-4 times as high as that of the external delays. All delays, even the smallest delay used (50 ms), contributed to a clearly measurable increase in the errors (about 15% at 50 ms), growing linearly with the amount of delay. The experiments also showed that amount of control movements, and thus workload, are more strongly influenced by delays than the errors. This is consistent with the results of Cooper, Harris and Sharkey (1975) who found that differences in steering behaviour may occur even without alteration of the performance.

3.6 UAVs

Research on UAVs control can be divided into two categories: vehicle control and sensor control. This division may be a bit artificial: For a UAV operator both vehicle and sensor controls often have an almost indistinguishable effect on the resulting sensor image that serves as the operator's feedback. Flying in a straight line while rotating the camera may result in comparable optic flow as flying a curved path with the camera steady. One difference in practice will be that the vehicle will respond much slower than the sensor.

In his thesis on UAV handling qualities, Thurling (2002) cites the *RPV Flying Qualities Design Criteria* (Prosser & Wiler, 1976). "The authors expected the stability and response characteristics of an RPV to be different from a piloted aircraft. With the pilot removed from the proprioceptive feedback cues in the cockpit, traditional values for response parameters may not apply." In Thurling's study, with the NASA twin-engine Utility UAV and pilots as UAV controllers, 189 ms is about the maximum additional time delay that can be allowed for an uncompensated system. With this amount of delay, five out of the six operators involved in the study rated the UAV as level 3 (Cooper-Harper rating 7-9). More results like this can be found. Hall et al. (2001), for instance, found that Cooper-Harper ratings of operators controlling a UAV camera are significantly influenced by latencies of 300 ms and higher.

A model study (with a fairly simple UCAV model) by Dougherty (2002) shows that unaided laser designation by the controller of a UCAV leads to errors for maneuvering targets. The errors depend on the amount of latency, and the speed and maneuvering type (constant velocity, accelerating) of the target. UCAV-GCS delays of 300 ms lead to designation misses of around 70 ft.
Apparently, 200-300 ms is about acceptable, but not more. Van Erp & Kappé (1998) explored much longer delays. They had subjects control an image sensor using a radar display that showed the sensor's footprint. The authors found that search time increased by 250% for 1 s delay, by 350% for 2 s and by 400% for 4 s of delay. These data are an average over the (low) update rates used in the experiment (0.5, 2 and 4 Hz) compared to the control condition with 30 Hz. The results also show that the distances 'traveled' by the camera's footprint did not increase as fast. Therefore, a large part of the increase in search time results from slower control movements, whereas a smaller part results from less efficient control movements (overshoots).

A number of experiments involved a situation in which both the UAV and its sensor were controlled by a UAV operator, using head-coupled control for the sensor: A head-tracker translates head movements in control instructions for the UAV sensor the images of which are presented on a UAV. Grunwald, Kohn & Merhav (1991) using a lag of 500 ms in the head-coupled loop in a UAV simulation experiment found only a small influence (4% higher error scores) on platform control but a large impact on head movements. Other researchers (De Vries & Padmos, 1997) found that adding 50 ms delay to the UAV imagery already delayed by a simulator-determined delay of 70-150 ms increased UAV control errors by about 20%.

In an experiment where a UAV operator using a head-coupled camera performed a patrolling task (Van Erp & Van Breda, 2001; Van Erp & Van der Dobbelsteen, 1998a; Van Erp & Van der Dobbelsteen, 1998b), most tasks were negatively influenced beyond 500 ms. With a one second delay, one of the search tasks (finding the location of six oil rigs) took more than twice the amount of time to finish and it took more than five times with a delay of 4 s (see Figure 14, left-hand panel). Not all performance indicators were found to be as sensitive for transmission delays. For one indicator measuring the standard deviation of the UAV camera pitch and hence the amount of its activity, only a delay of 4 s sufficed to yield a significant decrease in performance (see Figure 14, right-hand panel).

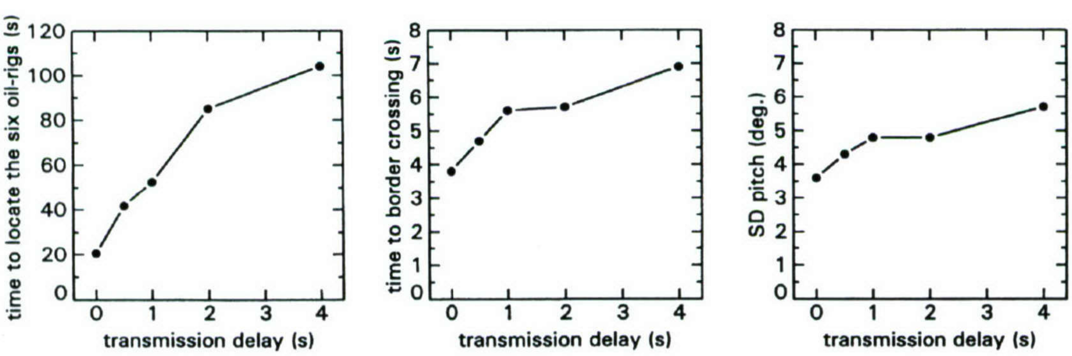


Figure 14 Data from a UAV patrol experiment by Van Erp and Van der Dobbelsteen (1998a). Search performance is indicated by three different indicators, from left to right: The time it took to locate a configuration of 6 oil rigs (the configuration was much larger than the field of view of the camera), the time it took to react to a penetration of the oil rig area by a ship and the standard deviation of the camera's pitch, a measure that describes the amount of activity of the camera.

4 Solutions

4.1 Adaptation & training

Vehicle controllers can often learn to adapt to the behavior of their vehicles. By means of experimentation, training, and extensive exposure to the system its characteristics can be more or less internalized and the vehicle can be partly controlled in an open-loop way (feed-forward). The control lead generated by the controller comes at the cost of an increased workload and it has its limits. Nevertheless, it is almost always fruitful to train extensively.

Ricard (1995) tested the number of trials necessary to reach criterion level performance in controlling pitch and roll of a simple airplane model. It appears that for small delays (less than 200 ms) the same performance can be achieved as for zero delay with sufficient training. Ricard found that various compensation schemes could accelerate the training time considerably (see Figure 15).

Other researchers (Foulkes & Miall, 2000) studied the effects of training as well. Though they report significant improvement in errors (about 20% less errors after training for a 300 ms delay and 15% for a 200 ms delay) they do not confirm Ricard's finding that the delays can be compensated totally. In fact, even after prolonged training the subjects in the 200 ms delay group still had a 60% higher error score than the no-delay group.

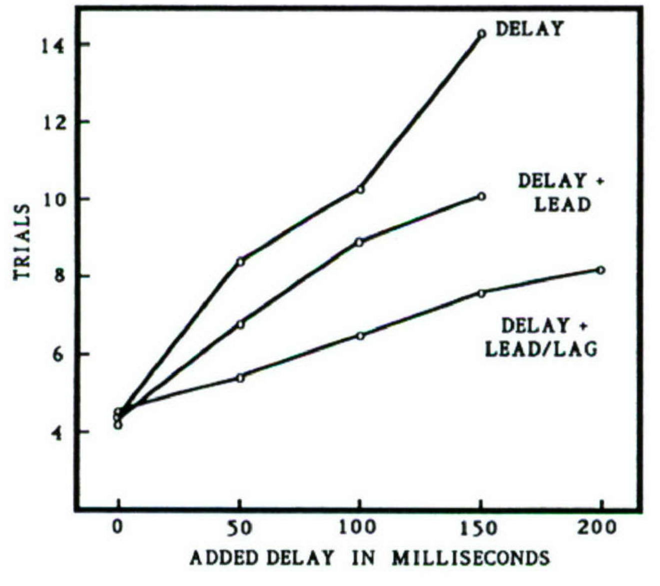


Figure 15 Number of trials required to reach to criterion performance for three different systems (a delayed system and two delayed systems with added filters) as a function of added delay (Ricard, 1995). In each case, the same level of performance is achieved, but the amount of training (and probably effort) involved varies with the delay.

4.2 Filtering and prediction

Quite often filtering of the control signals leads to an improvement of operator performance. Some filters, like a low-pass filter, prevent the occurrence of Pilot-Induced Oscilations (PIOs) because they cause an initial decrease of the acceleration of the response on a given error signal: they lower peak gain.

A good example of a delay-compensating filter is the so-called *lead-lag* filter. An example of such a filter (Van de Vegte, 1990) and its Bode plot is given in Figure 16. Its transfer function is:

$$f(s) = \frac{t_1 t_2 s + (t_1 + t_2)s + 1}{t_1 t_2 s + (t_1 + t_2 + t_{12})s + 1}, \tag{1}$$

with $t_1 = R_1 C_1$, $t_2 = R_2 C_2$, and $t_{12} = R_1 C_{12}$. The origin of the name of the lead-lag filter is clear from the phase diagram: Higher frequencies get a phase lead, whereas the lower frequencies get a phase lag. The amplitude diagram shows attenuation in the midrange while low and high frequencies are not attenuated (notch filter). With an optimal choice of parameters, this behavior can deal with the delay problem. The phase lead works as a kind of predictor, projecting part of the control response into the future, which to some extent, compensates for the delay.

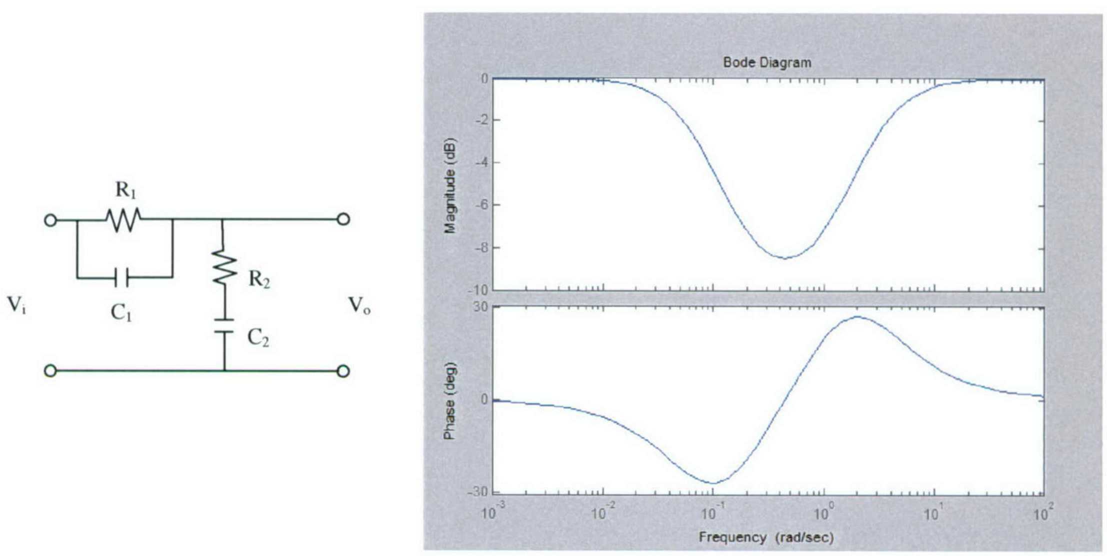


Figure 16 Electronic circuit example of a lead-lag network and its Bode plot. The members of the lead-lag family look similar to this example, but the specific location of the amplitude notch and their depths as well as those of the phase lead and lag lobes depend on the specific values of the parameters (in this case R_1, R_2, C_1, and C_2).

How does such a filter improve the operator's performance? Using the simulation set-up shown in Figure 17, we compare the simple operator/vehicle/delay system we encountered earlier (Figure 12, reflected in the upper part of Figure 17) with a system in which the operator's control output is filtered by a lead-lag filter. In Figure 18 the response of both systems with a varying amount of delay to a step input (for instance the requirement to suddenly change flight levels) is shown. The response to a sine wave input with varying frequencies is given in Figure 19. Clearly, the filtered system is far more robust and less prone to PIOs. The first panel of Figure 18 shows that it is

important to tune the filter to the amount of delay and the typical frequencies in the control regime. An incorrect choice may result in a response that is less adequate than the uncompensated system.

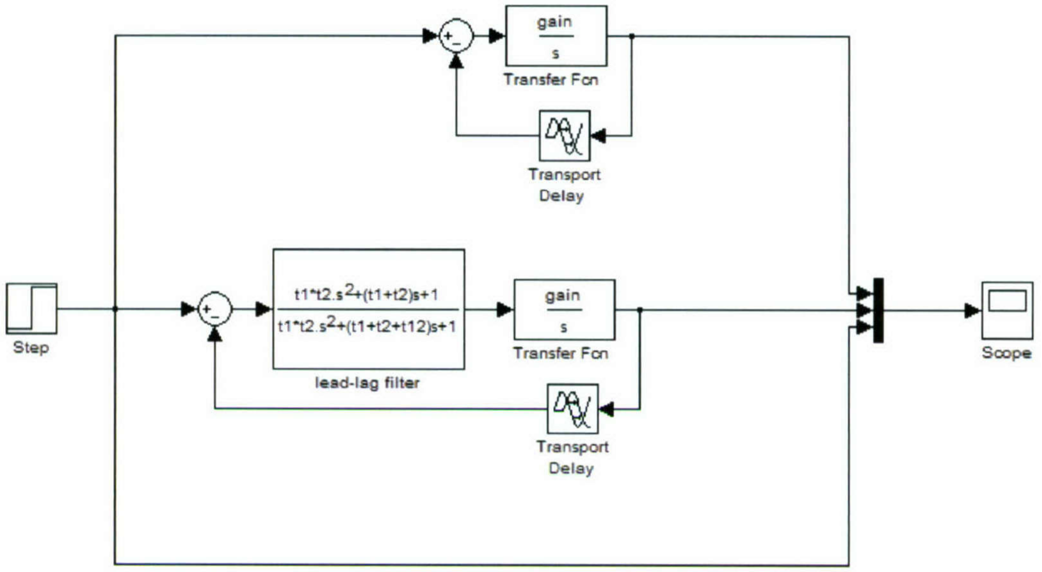


Figure 17 A MatLab Simulink model used to compare a simple delayed system, in this case an integrator with a delay on the feedback line, with the same system in which the control output of the operator (modeled by the comparator) is filtered with a lead-lag filter.

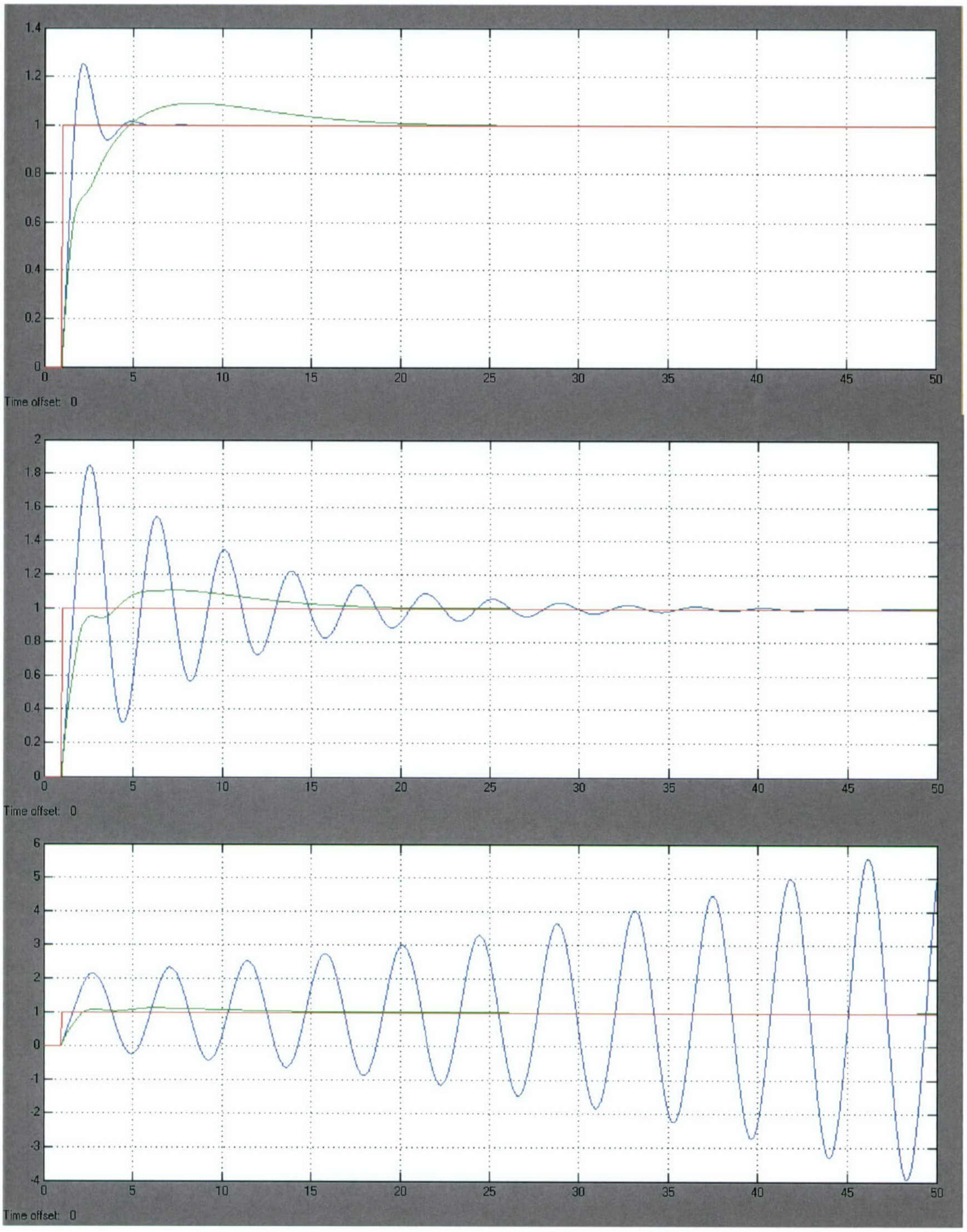


Figure 18 Output of the model of Figure 17 for delays 0.5, 0.9 and 1.1 s, respectively. The other values used in the model were: gain = 1.5, $t_1 = 5$, $t_2 = 1$ and $t_{12} = 10$ s. The input function (a step function) is shown in red; the result with the unfiltered operator response is shown in blue, while the filtered response is shown in green. Note that the vertical scale is different in each graph.

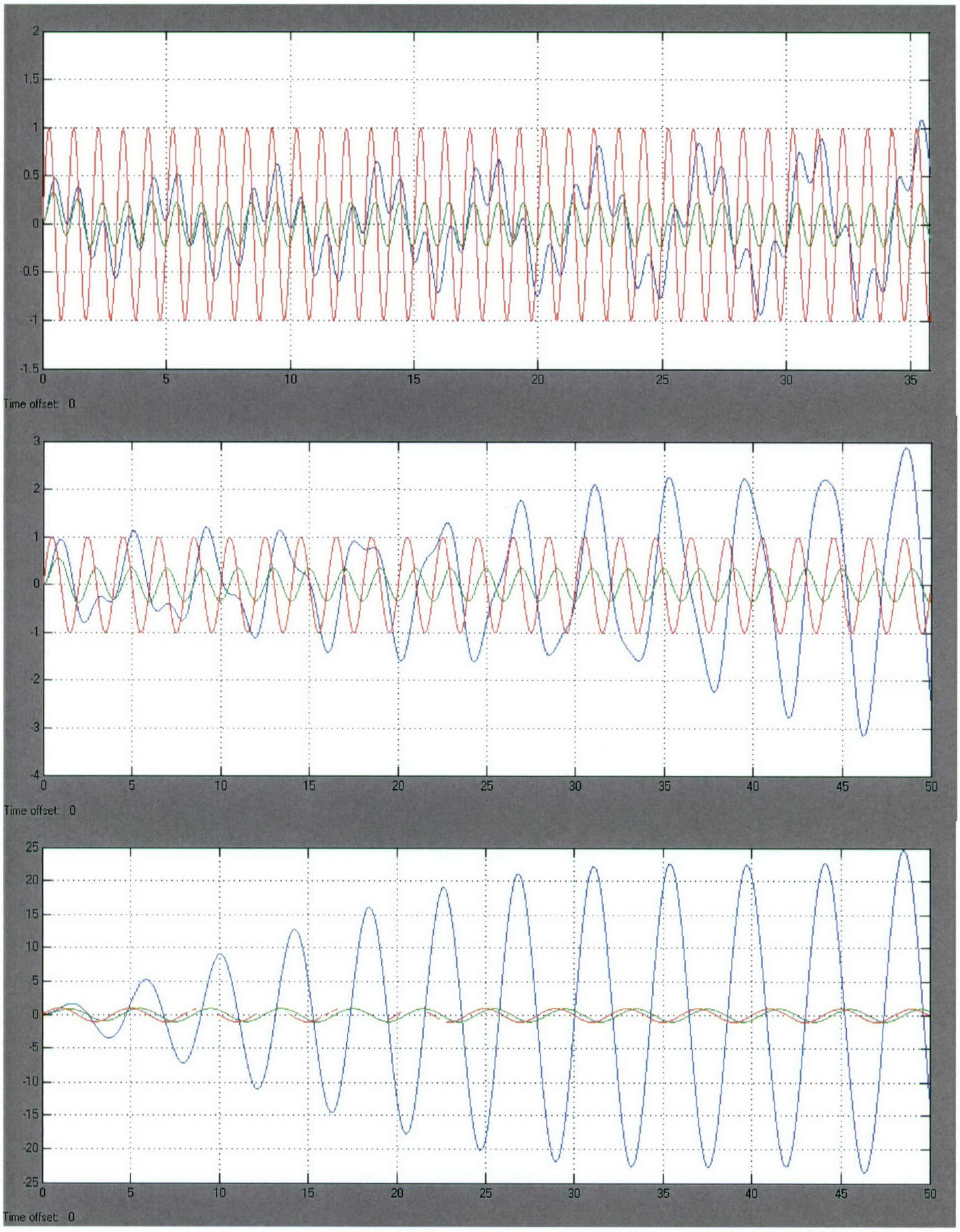


Figure 19 Output of the model of Figure 17 with a sine wave as input functions. Shown are results with input sine frequencies of 1, 0.5, and 0.25 Hz, respectively. The other values used in the model were: gain = 1.5, t_1 = 5, t_2 = 1 and t_{12} =10 s. The input function (a sine function) is shown in red, the unfiltered response is shown in blue, and the filtered response is shown in green. Note that the vertical scale is different in each graph and that the horizontal scale of the first graph differs from the others.

Of course, with a real human operator in the loop, results will be different. The reason is that human operators themselves are more complex than the comparator in Figure 17, and may be able to generate some lead, just as the lead-lag filter does.

Various filters have been tried and are described in the literature and most of them are able to compensate for considerable delays.

In the research mentioned in Section 4.1, Ricard (1995) found that lead-lag filtering not only may improve performance, but that it also decreases skill acquisition time considerably.

Shafer, Smith, Stewart and Bailey (1984) tested two PIO filters (scarcely described in the article) that are used in the space shuttle. Using two NASA test aircraft and trying various parameters of their filters, they found that they could lower the Cooper-Harper rating (see Figure 13) with 3 points even with an added delay of 165 ms.

Crane (1983) examined various systems with a delay of 108 ms and found that all five test pilots that took part in his simulator experiment benefited from delay compensation, some pilots even performed better with the delay compensated system with added delay than in the uncompensated baseline system without added delay.

Sobiski and Cardullo (1987) claim that lead-lag filtering as performed by Ricard and Harris (1980) represents suboptimal compensation. Apart from a lead-lag filter they test a predictive method in which the state transition matrix is applied in the feedback loop to compensate for time delays. In an experiment in which participants were required to stabilize an attitude indicator (artificial horizon display), they did not find positive effects of lead-lag filtering, but their own method appears to compensate for delays of up to 800 ms. Their lead-lag filter differs from the one in Equation 1, though. They used filters of the form:

$$f(s) = \frac{\tau_n s + 1}{\tau_d s + 1}, \tag{2}$$

which, according to Feedback Control Systems textbook author Van de Vegte (1990), is called a *phase lag* filter; apparently definitions vary. The filter has a Bode plot that differs considerably from that of the lead-lag filter of Equation 1. An additional note: The Sobiski and Cardullo study is a study of the compensation of the delayed visuals of a simulator. Delays were only present in the feedback part of the loop and not in the control part as would be the case for a UAV. The prediction used in their method is a prediction of the future state of the simulator visuals corresponding, of course, to a future state of the simulated vehicle, which would be hard to do for the real imagery of a UAV (however, see next section).

The results of Sobiski and Cardullo are confirmed in a study by Cardullo and George (1993). They compare the delay compensation offered by a lead-lag filter (again of the type of Equation 2, not 1) with that of a McFarland predictor (McFarland, 1988) and the Sobiski and Cardullo (1987) predictor. This study was a model study and did not use human operators as Sobiski and Cardullo did, but modeled them by a transfer function. The results were comparable: The predictor schemes are able to compensate fully for delays up to 400 ms, and at 800 ms perform only slightly worse than the non-delayed system. In a recent paper (Guo, Cardullo, Houck, Kelly & Wolters, 2004), the predictive methods were elaborated using either a Kalman estimator or a state space predictive filter and considerably improved, as the described model study seems to indicate.

In research specifically aimed at UAVs (Thurling, 2002), a system compensated with a model-based prediction scheme, 389 ms was the maximum useable delay. Thurling used a model-based prediction, because simulations showed it to be better than a lead-lag filtering scheme. The compensated system, the NASA twin-engine Utility UAV, had a good Cooper-Harper rating: five out of six operators rated the UAV as a level 2 system (flyable with some difficulties, Cooper-Harper rating 4-7), averaging a C-H rating of 5.3. This is much better than the uncompensated system with a delay of 189 ms which was rated as a level 3 plane. Five out of six operators rated the UAV as level 3 (Cooper-Harper rating 7-9). Additionally, pilots stated that the compensated system did not show PIO tendencies and workload was much lower with the compensation than without. Improvements in objective measurements were not so univocally positive. One of the two error measurement variables used in the experiment was improved with prediction, but the other was not. Thurling hypothesizes that shortcomings in the prediction scheme were most likely due to inadequacies in the linear model used to generate the predictive display or unmodeled disturbances such as wind gusts and turbulence.

More evidence on the positive effects of prediction can be found in two studies on the networked simulation protocol DIS (De Vries, 1999; De Vries & Kappé, 1999). In these studies, it was found that internal delays (delays within a simulator) contributed two to four times as much to formation flying errors as external delays (delays between two simulators). The difference between the two types of delay in this experiment was that the internal information, though being processed at a high update rate, was not compensated for the delay whereas the external data stream, sent at a low update rate, was. The position information of the external vehicle was extrapolated using a second order predictive motion scheme (constant acceleration). Though prediction clearly helped lowering average errors, it did increase the frequency of the error patterns, indicating either a higher sensitivity to noise or a higher workload.

In a study aimed at a UAV sensor operator, Van Erp and Kappé (1998) reported very good results of camera movement prediction. Search times were much lower (by roughly 50%) with prediction and increased less strongly with increasing delays (see Figure 20).

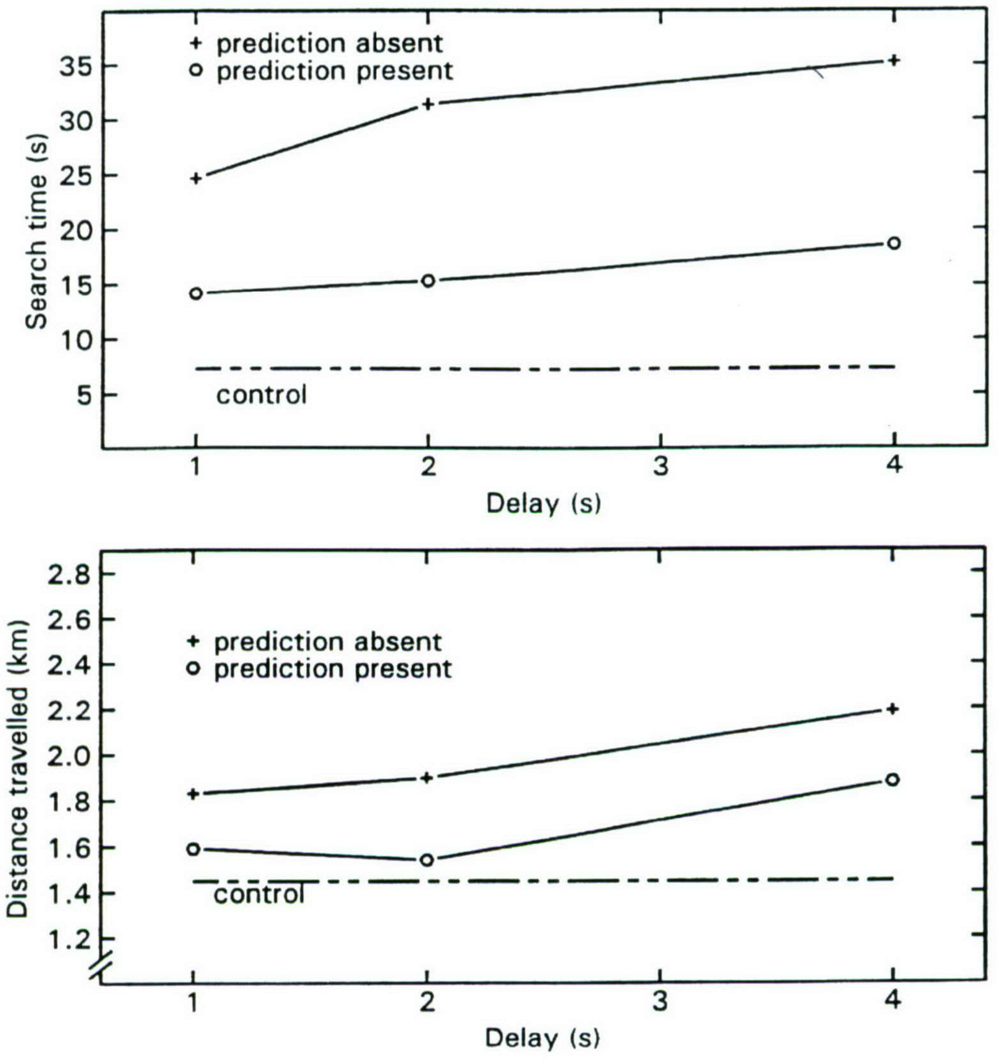


Figure 20 Data from Van Erp and Kappé (1998). Search time and search efficiency (as indicated by the distance the camera footprint traveled to reach its goal) as a function of transmission delay. Note that these results are an average of several low update conditions. The control condition has both a high update rate and a zero added transmission delay.

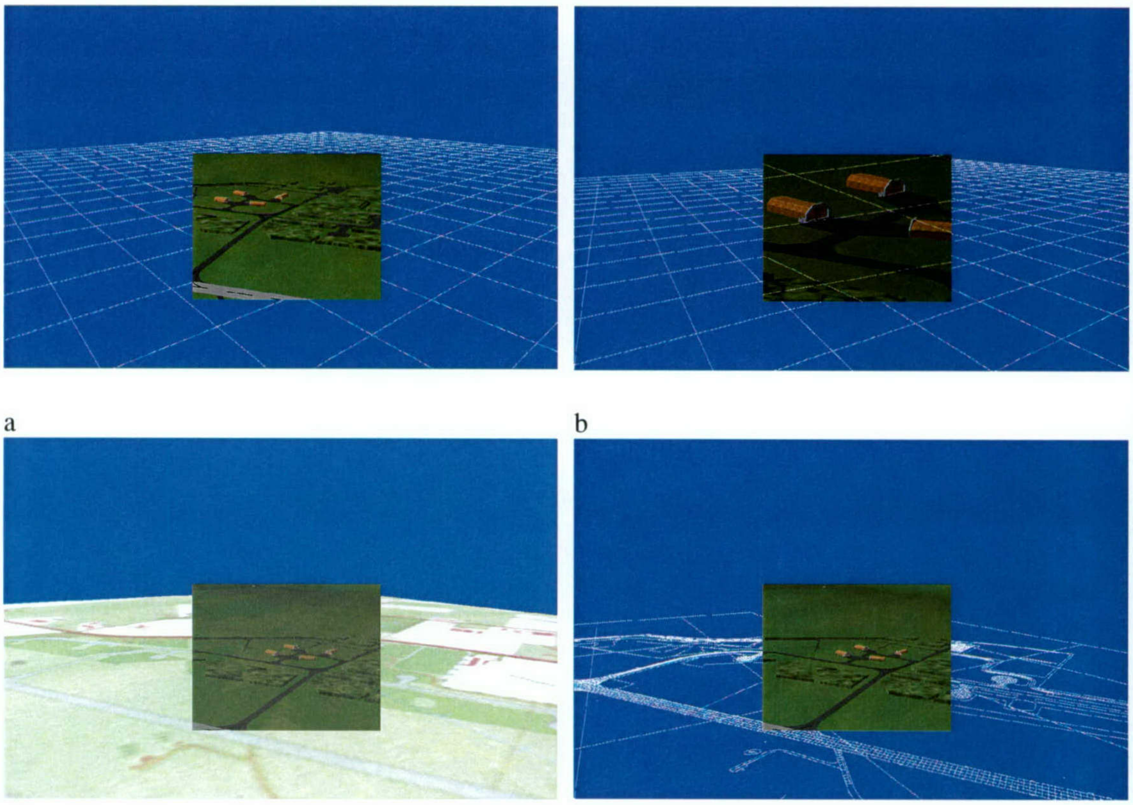
4.3 Augmented displays

Augmented displays techniques are closely related to prediction techniques. The basic idea is that the delayed visuals are embedded in imagery that is not delayed, i.e. the display shows the context of the visuals as if it was taken with a sensor that responds immediately to the operator's control instructions.

In this way, not only the operator's situational awareness is improved by placing the image in its geographical context, but the PIO tendency of the operator-UAV system is greatly reduced as well. The latter is possible, because most of the operator's control task is now moved to the non-delayed area. Examples of augmented displays can be seen in Figure 21 and Figure 22, imagery augmented with 2D information in a perspective presentation, and with mixed 2D/3D information, respectively.

The information with which the UAV imagery is augmented has to be available of course. The required extra information ranges from almost none Figure 21a, to area maps Figure 21c, and to complete 3D models of the theatre of operations (Figure 22b,d). Nowadays, even the latter information is relatively easy to obtain.

Another requirement that is less easily obtained is a correct prediction of the sensor's future state after the current operator's control instructions have arrived. This means we need a very accurate model of the vehicle and its sensor, as well as of their environment (wind, turbulence).



a b

c d

Figure 21 Screen shots from the TNO Human Factors UAV demonstrator. In the centre of all panels the (simulated) camera image of a UAV sensor can be seen. *a:* The camera image is surrounded by a grid, generated at the GCS which predicts the effects of (delayed) camera control movements. *b:* The grid can overlay the camera image and can in this way convey information on the zoom state of the camera. *c:* A perspectively projected map used as background. *d:* All kinds of data can be used to augment camera images. In this case a simulator database is shown in wireframe mode. Again, this can be used to overlay the camera image as well. In this way underground pipelines can be indicated, for instance.

In an experiment performed at TNO by Veltman and Oving (2003), participants acting as the sensor operator of a UAV inspected roads and edges of wood using the sensor with and without the aid of a 3D map. A 2D map with the same information as the 3D map was available in all conditions (see Figure 22). With the 3D map, the participants were able to inspect larger areas, especially when the task became more difficult due to time delays and low update rates, were better able to perform an additional task, and reported lower workload compared to the condition without the 3D map.

In our informal experience with the augmented display of Figure 22, the sensor can be easily operated with one to several seconds of delay.

As an interesting side note: predictive augmented displays have been intensively tested for application in tele-robotic applications in space for some time now. Quite often delays can run in the several seconds, and great improvements have been reported for using augmented displays (Lane et al., 2002; Lane, Carignan & Akin, 2000; Lane, Carignan & Akin, 2001).

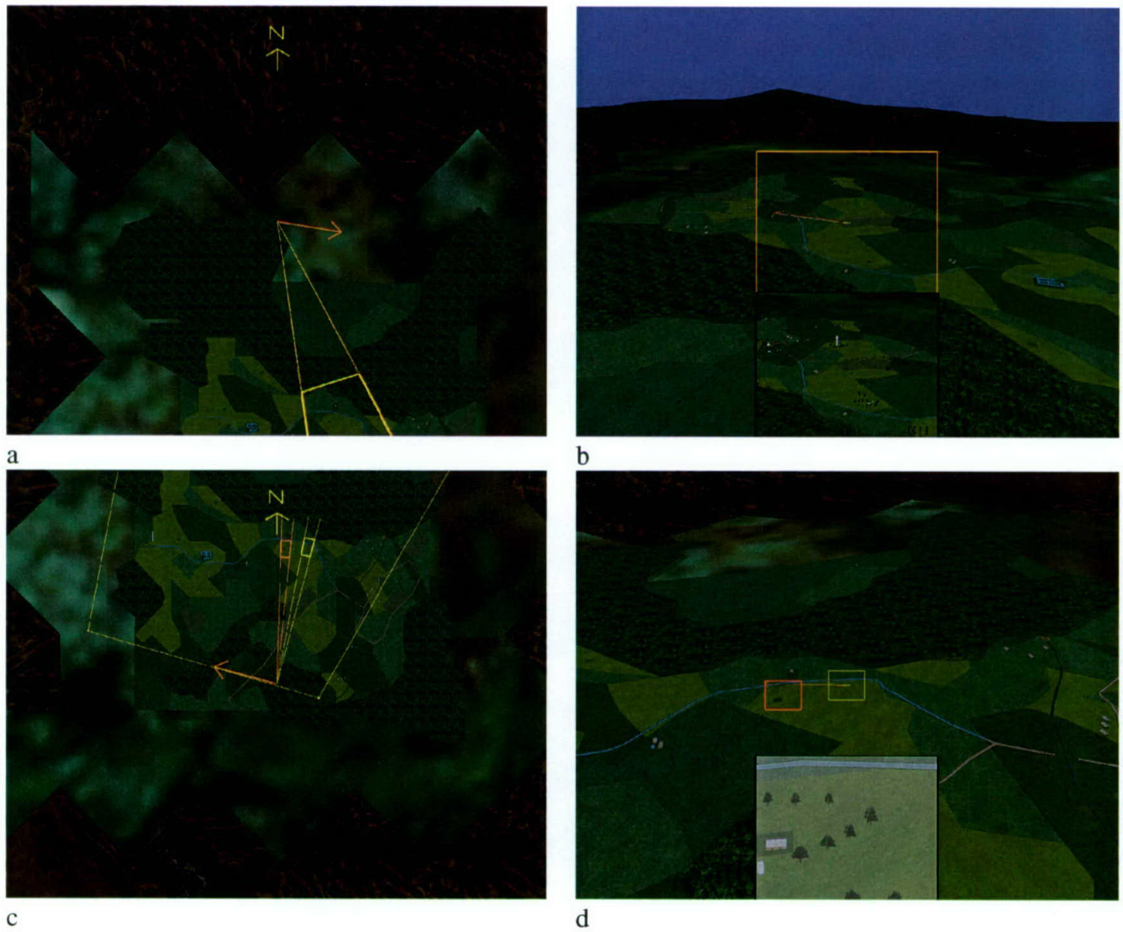


Figure 22 Screen shots from the experiment of Veltman and Oving (2003). ***a:*** a 2D situation display showing the camera footprint, i.e. the part of the world visible on the camera display. Overlays in two colors are present: The yellow color indicates the predicted camera footprint; the orange color indicates the position of the footprint corresponding to the current camera image. In panel *a* and *b* these elements overlap and can not be distinguished very well; in *c* and *d* the camera is in motion and the colored elements can be clearly distinguished. ***b:*** a 3D situation display with the camera image as an insert at the bottom of the display. The situation corresponds to the situation depicted in *a*. ***c:*** the camera is zoomed in more (footprint gets smaller) and moves. The boxes indicate the part of the 3D database that is (orange box) and will be (yellow box) displayed. Due to transmission delays, predicted and current footprint do not coincide anymore. ***d:*** The 3D version of the situation depicted in panel *c*.

4.4 Image deflection

It is an option to show sensor imagery on an HMD or on a simulator projection dome and to use head-tracking to control the orientation of the sensor instead of manually controlling the sensor. The advantage would be that the situational awareness of the sensor operator would be improved (where-you-look-is-what-you-get), although this purported advantage didn't show up in a previous study (De Vries, 2001).

The problem is, data link latency does not only cause head-coupled images to be displayed too late, but they are also displayed in the wrong position, depending on the speed of the head movements. If the latency is given by dt and the head motion is v deg/s then the misplacement of the image is $v\ dt$ deg. Since head motions can be hundreds deg/s the images may be off by tens of degrees. Because head motion varies considerably, the misplacement of the image in space does vary considerably as well, yielding a very unstable localization of the image.

Various researchers (So & Griffin, 1993; So, 1997; So & Griffin, 1997; Van Erp & Van der Dobbelsteen, 1998a; Van Erp & Van der Dobbelsteen, 1998b) have conceived and tested a comparable solution to this problem. In (So & Griffin, 1993) several other researchers are cited as well. There are even some patented solutions (Allen, Portoghese, Hebb & Breglia, 1984; Lee & McCreary, 1984) that all apply more or less the same principle.

The solution requires knowledge of the amount of latency, which is usually easily to obtain from signal time stamps. With knowledge of the latency, it is easy to present the image at the correct position. This means that the image is not always in front of the observers. Though this means that the image frame is lagging behind the head movements, its contents are displayed at the correct position (at least when these contents are stationary). All researchers found this method to be very successful. So and Griffin (1993) reported that subjective difficulty rating were largely unaffected by lags of up to 400 ms if deflection and prediction was used. So (1997) found that image deflection, combined with phase lead filters, produced a tracking performance unaffected by lag that amounted in his experiment to 140 ms.

Van Erp and Van der Dobbelsteen (1998b) found a considerable performance increase due to image deflection (or "delay handling" as they called the method). The improvements of delay compensation on tasks performed with a set of delays ranging from 0 to 4000 ms averaged 15% for one particular task and 40% for another. In a follow-up experiment (Van Erp & Van der Dobbelsteen, 1998a), they did not find much improvement using this compensation technique if the images were zoomed-in.

The deflection technique could be combined with the augmented display of Figure 22b. The small sensor window showing the delayed image could be shown at a position corresponding to that of the sensor at the time the image was actually made.

5 Conclusions

Roundtrip delays in a UAV-GCS configuration range from a minimum of about 100 ms in simple line-of-sight situations to more than 1600 ms while using geostationary satellites and taking other sources of delay into account. This is a conservative estimation. Much larger delays are quite possible.

Both basic and applied research experiments generally point to a delay of 100 ms as an amount that has a measurable impact on human performance. Aviation-related literature and regulations indicate that a delay of 250-300 ms may be regarded as the maximum value from a flying handling qualities viewpoint.

In the past, the RNLAF has indicated to be interested in UAVs that have a strategic operating range of more than 1000 km. This means that line-of-sight datalinks are out of the question and geostationary satellites will be the preferred type of connection, until the moment arrives that a flexible network of low-flying relay stations is in operation and available for RNLAF operations.

Given the preferred datalink and its corresponding delays, UAV handling qualities will suffer considerably, to the point of becoming almost impossible to handle directly.

Using techniques such as filtering and predictive displays, handling qualities can be made acceptable for delays of up to 400 ms, though even extreme values of 800 ms are claimed.

However, the delays caused by geostationary satellite connections will be so high that even with these techniques direct control will be extremely difficult.

A distinction between the critical, high-gain task of vehicle control and the less critical, lower gain task of sensor control should be made. Whereas vehicle control with all possible augmentation is probably not acceptable beyond 400 ms delay, augmented sensor control may be quite acceptable well within the seconds range.

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7 Acronyms

AOB	Advanced Operations Base
FOB	Forward Operations Base
GCS	Ground Control Station
GDT	Ground Data Terminal
GPS	Global Positioning System
HALE	High Altitude Long Endurance
HF	High Frequency
HQ	Headquarter
LEO	Low-Earth Orbit
MALE	Medium Altitude Long Endurance
MOB	Main Operations Base
NSWC	Navy Surface Warfare Center
PIO	Pilot Induced Oscillation
RF	Radio Frequency
TCS	Tactical Control Station
UAV	Unmanned Aerial Vehicle
UCAV	Unmanned Combat Aerial Vehicle
UHF	Ultra High Frequency
VHF	Very High Frequency

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Figure 10:	NASA Dryden Flight Research Center Photo Collection, NASA photo ED01-0230-1 by Nick Galante
Figure 11:	http://www.geocities.com/rpvbt/index.htm and a PowerPoint presentation of the 101th Remotely Piloted Vehicles battery, Royal Dutch Army.
Figure 13:	NASA. http://flighttest.navair.navy.mil/unrestricted/ch.pdf
Figure 14:	Van Erp and Van den Dobbelsteen (1998b)
Figure 15:	Ricard (1995)
Figure 20:	Van Erp and Kappé (1998).

9 Signature

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15. ABSTRACT (MAXIMUM 200 WORDS (1044 BYTE))

UAV's (Unmanned Aerial Vehicles) are remotely controlled. Delays in the datalinks are to be expected, potentially influencing the performance of the UAV operator. In this study, we examined literature on sources of delay, their effects on human performance, and potential solutions. Delays turn out in the range of 100 to 1600 ms. A delay of 100 ms usually leads to measurable degradation of human performance. Delays of about 250-300 ms often lead to unacceptable airplane handling qualities. Techniques such as filtering and predictive displays may extend the range of acceptable delays up to about 400 ms or more. Control of UAV sensors is considerably less critical than the UAV itself and compensation techniques will probably lead to acceptable performance with delays up to 1000 ms. Signal delays will not significantly impede control of the UAV in the case of line-of-sight connections or while using relay stations on or close to the earth. When geostationary satellites are used, delays will generally be so high that a UAV operator will generally operate in a supervisory role. Only the control of the sensors of the UAV, less critical than the control of the vehicle, may be handled directly by an operator.

16. DESCRIPTORS

IDENTIFIERS

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Unmanned Aerial Vehicles
delay
latency
control
compensation

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